COLLEGE OF ENGINEERING

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Engineering Complex

TENNESSEE TECHNOLOGICAL UNIVERSITY
COOKEVILLE, TENNESSEE

Investigation of the Difficulties Associated with the Use of Lead Telluride and Other II - IV Compounds for Thin Film Thermistors

Final Report Under Grant
NGR 43-003-012

For the Period
January 1970 through May 1975

to

National Aeronautics and Space Administration
Langley Research Center
Langley Station
Hampton, Virginia 23365

from

Electrical Engineering Department
Tennessee Technological University
Cookeville, Tennessee 38501

W. D. McLennan
Principal Investigator

INTRODUCTION

This is the final technical report under NASA Grant NGR 43-003-012. This research has been concerned with solving the difficulties associated with the fabrication of a thin film thermistor for use as an atmospheric temperature sensor in the meteorological rocket sounding program. The NASA Technical Officer for this grant was Mr. Charles Hardesty at NASA's Langley Research Center. This report covers the period from January 1970 to May 1975.

THE THIN FILM THERMISTOR

STRUCTURE

A number of sensing materials and device structures were considered in the course of this investigation. The final configuration is shown in Fig. 1 and consists of six (6) layers of material which were vacuum deposited on a kapton* substrate 0.00025 inches thick. Two of these six layers were deposited on the back surface with the remaining four layers being deposited on the front surface. The composition of the six layers, their primary function, and appropriate comments are contained in the following list. (The numbers in parenthesis refers to Fig. 1)

(1) Quartz (SiO_2) - When quartz is deposited on a kapton substrate the stresses in the quartz film will cause the substrate to curl. This layer produces forces which counteract the forces produced by the quartz layers deposited on the front surface and therefore prevent the tendency for the substrate to curl.

* Kapton is a duPont tradename

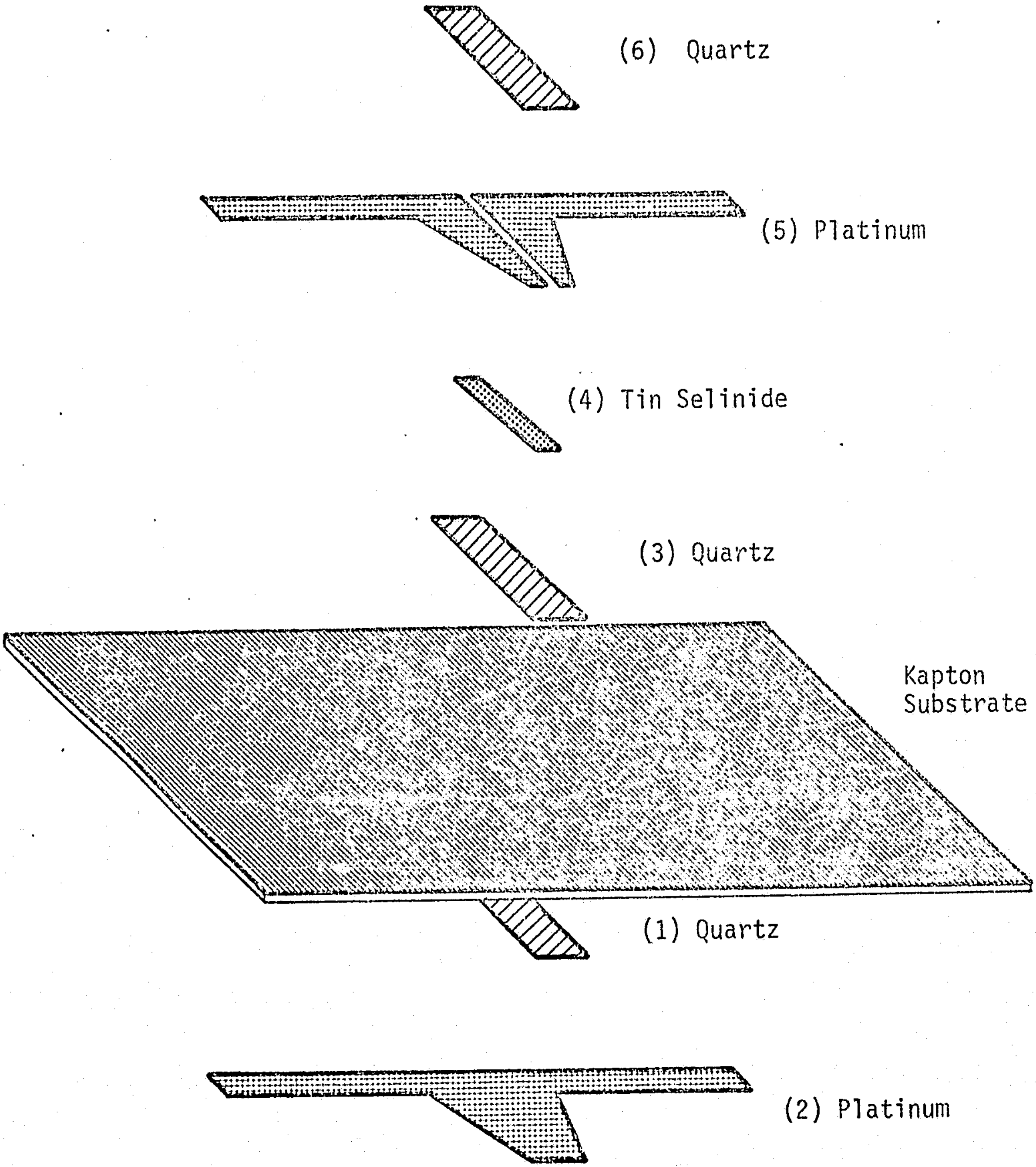

Figure 1. Thin film thermistor structure

(2) Platinum (Pt) - This platinum layer has the same size and shape as the device deposited on the front side of the kapton and acts as a radiation shield.

(3) Quartz (SiO_2) - The function of this layer is to isolate the sensing material from the kapton substrate. That is, it serves as the lower half of an encapsulating layer surrounding the sensing material. The need for and the effect of this layer was discussed in the 7th semi annual status report which covered the research period, December 1, 1972 through May 31, 1973.

(4) Tin Selenide (SnSe) - This is the sensing material. Tin selenide was one of the six compound semiconductors considered. The other five were the compounds of tin with tellurium and sulfer and the compounds of lead with selenium, tellurium, and sulfer. The initial phase of this development effort concentrated on the use of lead telluride as the sensing material because it had a lower resistance at room temperature than the tin selenide. However, the problem of migration between the lead telluride and the metal contacts could not be solved and the effort was shifted to tin selenide.

(5) Platinum (Pt) - The ratio of the electrical conductivity to the thermal conductivity is larger for platinum than for any other metal. For this reason platinum was chosen for the electrical contacts since it was necessary to thermally isolate

the sensing region of the device from the supporting shield. the actual sensing area of the thin film thermistor is defined by a 0.010 inch gap between the two contact pads.

(6) Quartz (SiO_2) - This last layer of quartz serves as the second half of the encapsulation and protects the sensing region from moisture and other contaminants.

FABRICATION

The six layers of material which form the thermistor were vacuum deposited from source material which was heated by means of an electron gun. The chamber pressure prior to the start of the deposition process was less than 10^{-7} Torr and increased into the high 10^{-6} or low 10^{-5} Torr range during the deposition. Since the kapton substrate was not self-supporting, it had to be wrapped around a 2 inch square glass substrate for support with a second substrate used to clamp the ends of the kapton. After the quartz and platinum layers had been deposited on the back side of the kapton, the sample had to be removed from the vacuum chamber and the kapton turned over.

The metal masks used to define the patterns needed for the simultaneous deposition of three identical devices were etched from 0.005 inch thick berillium copper shim stock using photo masking techniques. The 0.01 inch gap which defined the sensing region was produced by spot welding a 0.01 inch tungsten wire to the previously etch contact mask.

This resulated in a gap which defined the sensing region which had a uniform width and smoother edges than could be obtained with photo etching techniques.

The six layers which make up the device were deposited under the control of a minicomputer. A dissertation describing this controller and its capabilities is included as appendix I of this report. For further information on the fabrication process the reader is referred to appendix I of the 10th semi annual report.

TESTING

A constant temperature chamber was designed and constructed for use in calibrating the sensors at discrete temperatures. The construction of this chamber is illustrated in Fig. 2. A container, to hold the liquids used for the constant temperature baths was constructed of one inch thick bakelite. This container was sealed with silicone seal, surrounded on all sides by at least four inches of styrofoam, and inserted in an aluminum box which opened at the middle to permit access to the inner sample enclosure. The samples to be tested along with two platinum resistance reference thermometers were mounted in a copper enclosure which is supported from the top of the bakelite container. Electrical connections from the samples and reference thermometers pass through feedthroughs in the top of the copper enclosure and are then routed through a stainless steel tube which passes through the cooling bath.

In order to fit the resistance vs. temperature characteristics of the sensors to an equation of the form

$$\frac{1}{T} = A + B \log R + C (\log R)^3 \qquad (1)$$

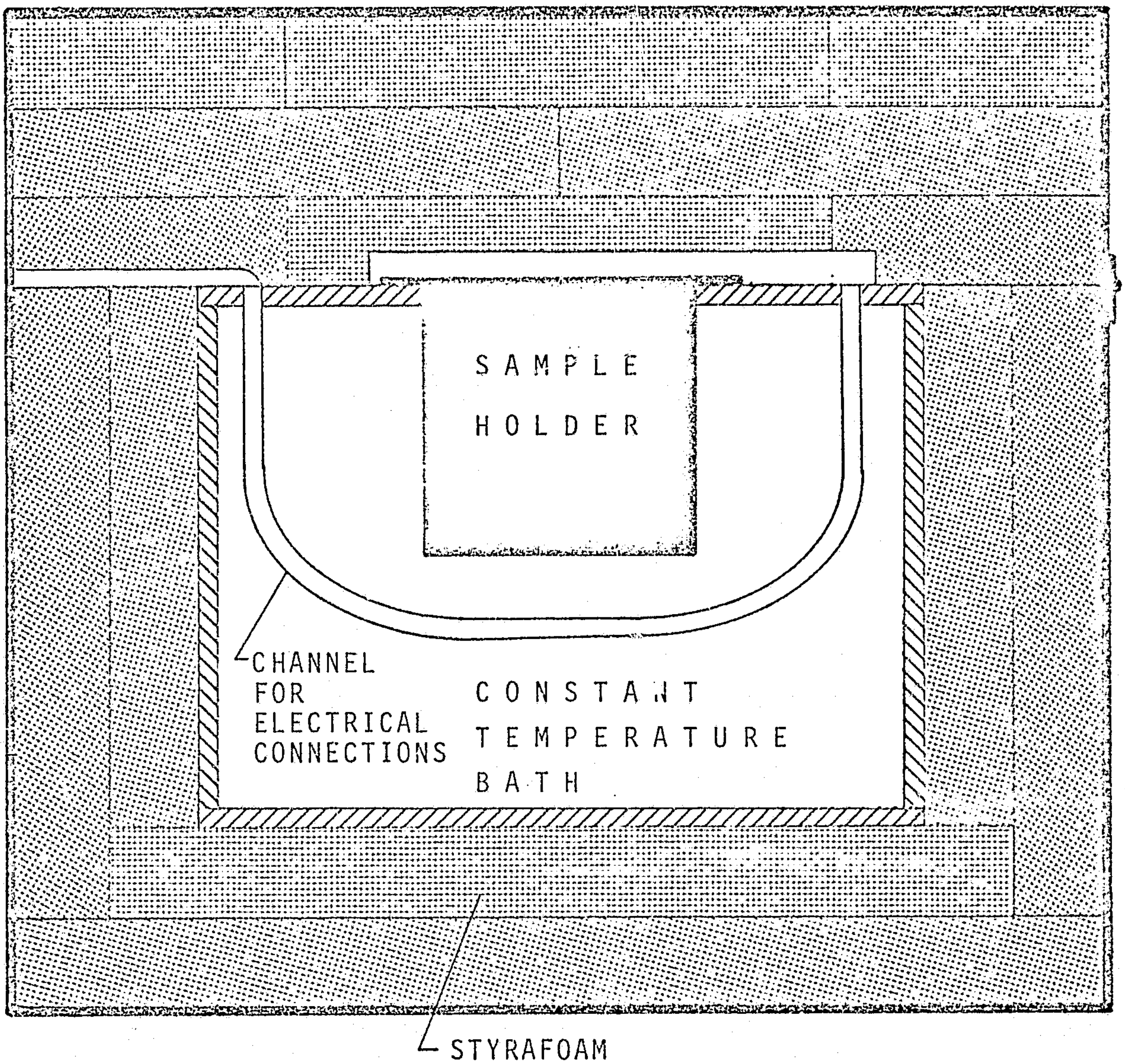

Figure 2. Illustration of constant temperature chamber construction.

data at three discrete temperatures was required. The temperature of a distilled ice water bath and the temperature of an acetone and dry ice bath were selected for two of these temperatures. Efforts to obtain a temperature bath having a temperature between these two were unsuccessful and therefore the room temperature in the laboratory was used for the third temperature.

During the measurement sequence the samples were sealed in the test chamber and measurements made at 5 minute intervals. Platinum resistance thermometer (PRT) FL-31 was arbitrarily selected as the standard for all subsequent comparisons. The resistance readings of a second PRT, FL-51, vs PRT FL-31 are shown in Fig. 3. These measurements indicate that the two PRTs are within 0.01 Centergrade degrees of each other for this group of measurements. The resistance of three representative thin film samples at room temperatures vs the resistance of PRT FL-31 are presented in Fig. 4. Based on this data, the resistance of PRT FL-31 which corresponded to 19°C was selected for one of the calibration points for the thin film samples. After the measurements at room temperature were completed, the copper container was surrounded with a distilled ice water bath and subsequently an acetone and dry ice bath. The resistance measurements at the three temperatures are given in Table 1.

After the chamber had been maintained at the temperature of the acetone and dry ice bath for two and a half days the temperature was allowed to increase. The difference in temperature between PRT FL-31 and PRT FL-51 as a function of the temperature of PRT FL-31, as the temperature of the box is returning to room temperature, is shown in Fig. 5. The spike

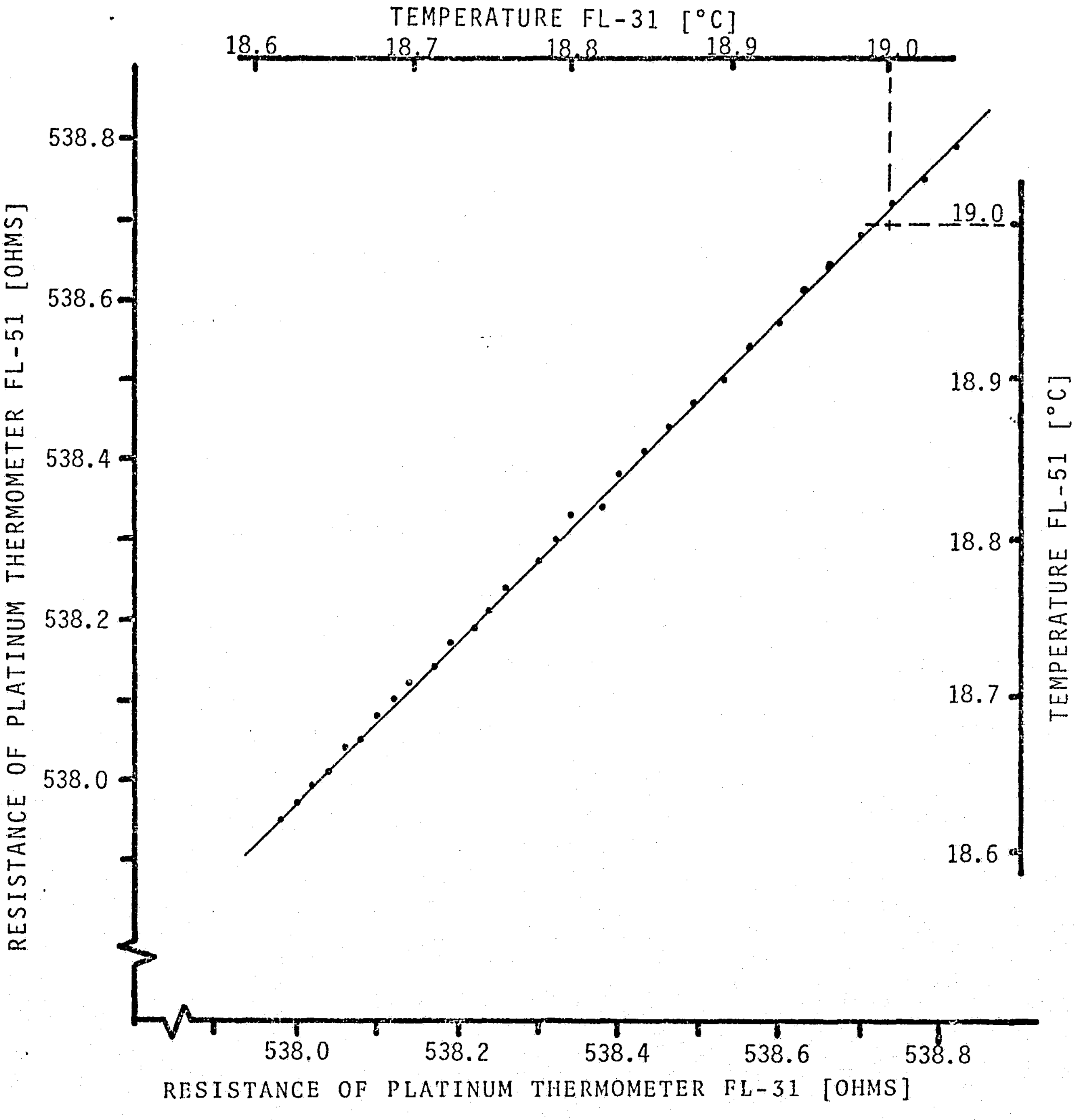

Figure 3. Comparison of the two platinum resistance thermometers (PRT) at room temperatures.

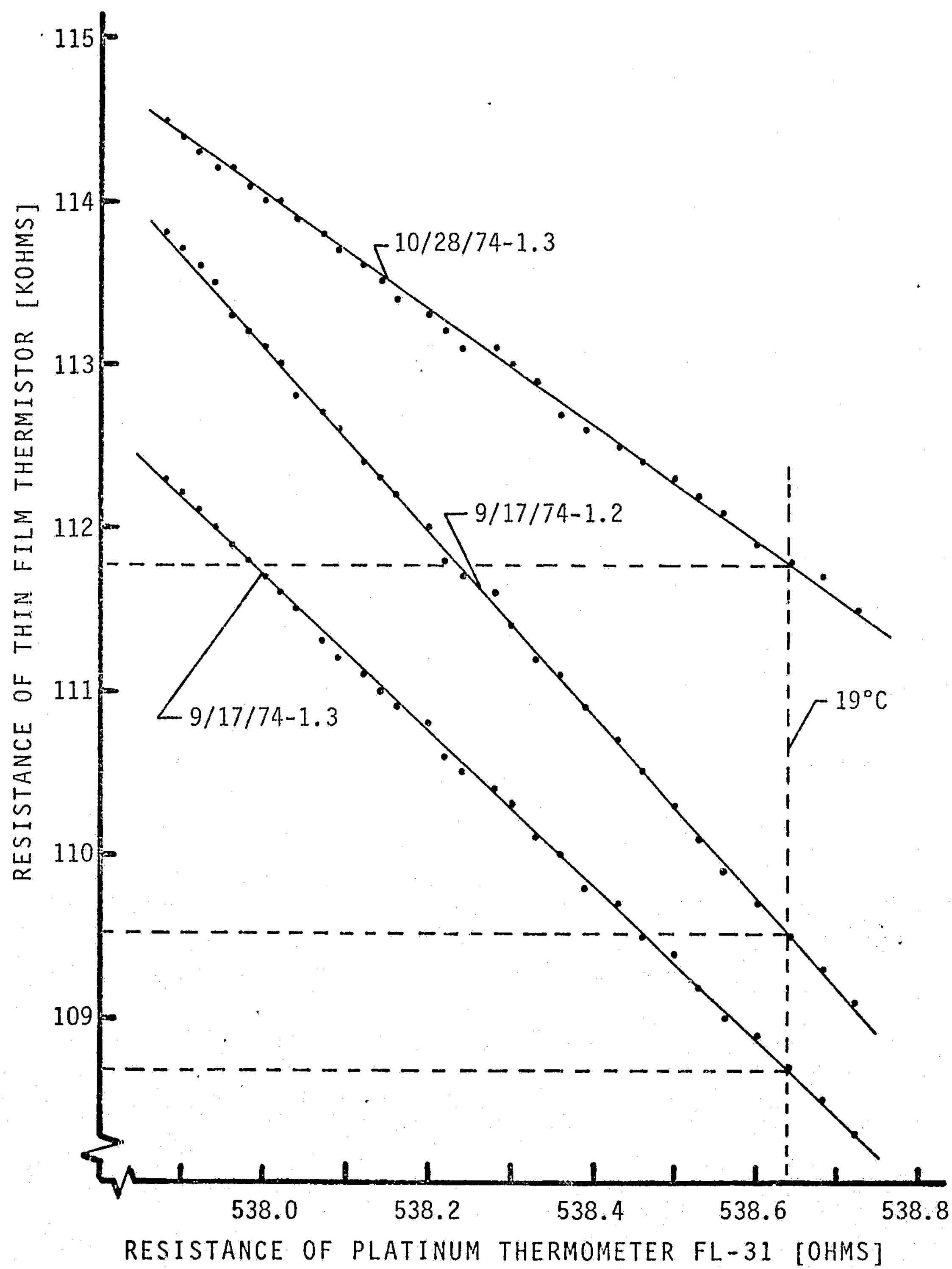

Figure 4. The resistance of three representative thin film thermistors as a function of the resistance of PRT FL-31.

TABLE 1

SAMPLE NUMBER	SAMPLE RESISTANCE [OHMS]		
	292.15°K	273.13°K	194.575°K
9/17/74-1.3	108,680	209,650	5,768,250
10/28/74-1.3	111,800	211,700	4,239,400
9/17/74-1.2	109,560	212,000	6,298,800
10/28/74-1.2	32,690	45,700	4,249,300
10/27/74-1.3	142,670	248,950	2,674,800
8/25/74-1.3	140,900	314,800	6,528,350
8/28/74-1.3	194,230	366,800	7,626,050

Measured resistance of thin film samples at selected calibration temperatures. (Data used for first set of computations)

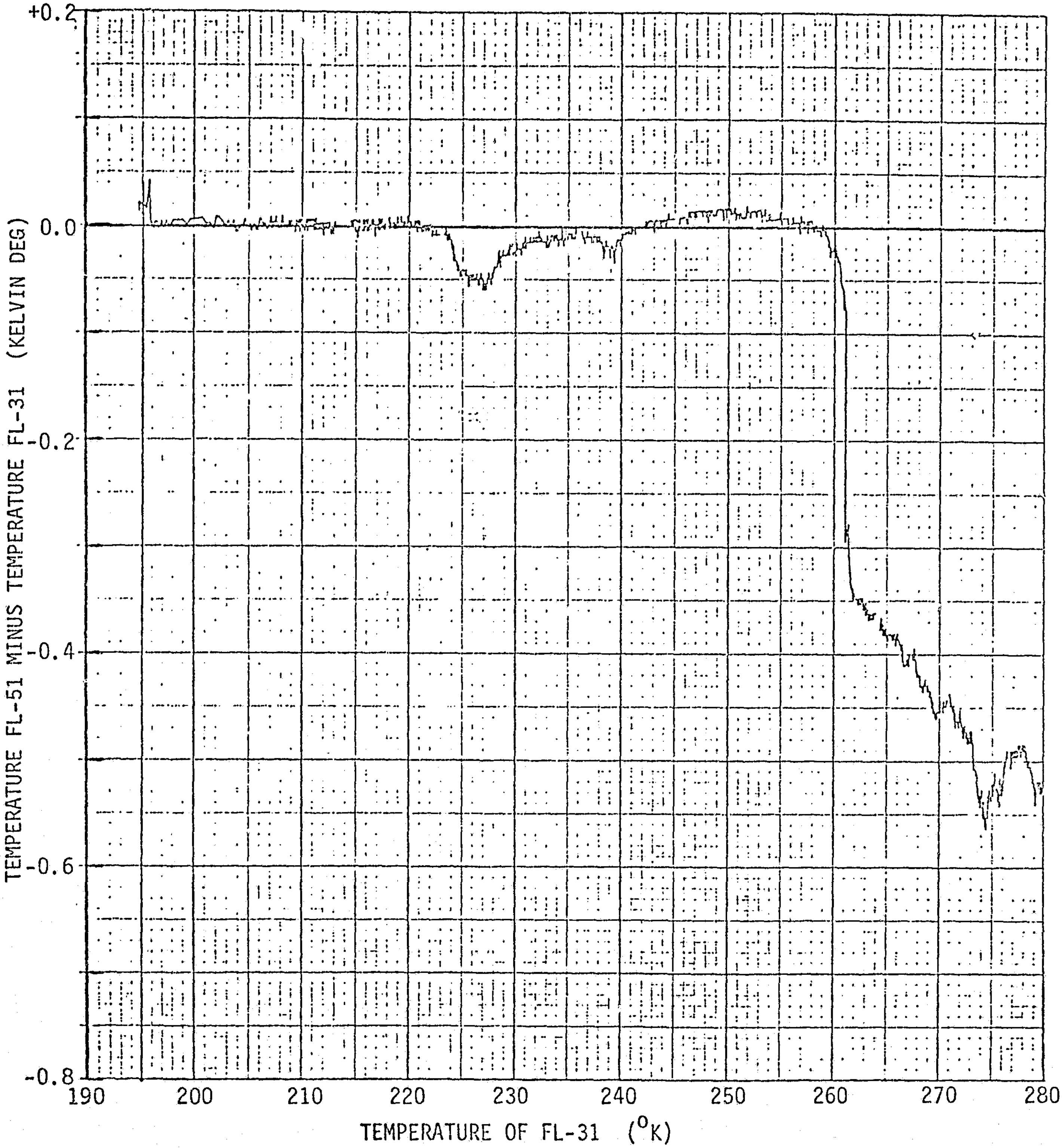

Figure 5. Difference in temperature between two platinum resistance reference thermometers as the chamber temperature is increasing. (Elapsed time is five (5) days)

on the curve at 195^{o}K occurred when additional dry ice was added to the bath. The result drawn from this curve is that the two PRTs were in agreement when the temperature of the chamber was fairly stable.

Using equation 1 and the data in Table 1 the three coefficients for each thin film sample were calculated. These values are given in Table 2. Efforts to correlate the data obtained from the thin-film thermistors with the data obtained from the PRT were not, at first, completely satisfactory. Figure 6 shows the temperature of PRT FL-31 vs. time. This curve is of value as a basis for evaluating the subsequent thin film thermistor curves. The results obtained from the thin film samples fall into three classes.

I. 10/28/74-1.3 Fig. 7
10/27/74-1.3 Fig. 8

These curves are in reasonable agreement with PRT FL-31, however, there appears to be an offset error.

II. 10/28/74-1.2 Fig. 9

These results are not satisfactory. Part of the problem might be due to improper coefficients. Subsequent measurements and calculations show that this is the case.

III. 9/17/74-1.3 Fig. 10
9/17/74-1.2 Fig. 11
8/28/74-1.3 Fig. 12

These samples show a continuous drift in resistance and therefore there is no possibility of calibrating them until their characteristics stabilize.

TABLE 2

SAMPLE NUMBER	COEFFICIENTS FOR EQUATION 1 [$°K^{-1}$] A	B	C
9/17/74-1.3	$1.0159x10^{-3}$	$1.3614x10^{-4}$	$5.3225x10^{-7}$
10/28/74-1.3	$1.9511x10^{-3}$	$1.2803x10^{-5}$	$8.4226x10^{-7}$
9/17/74-1.2	$8.1822x10^{-4}$	$1.6161x10^{-4}$	$4.6675x10^{-7}$
10/28/74-1.2	$-9.0988x10^{-3}$	$1.4397x10^{-3}$	$-2.1757x10^{-6}$
10/27/74-1.3	$4.4188x10^{-3}$	$-3.2286x10^{-4}$	$1.6964x10^{-6}$
8/25/74-1.3	$4.4646x10^{-3}$	$-2.6194x10^{-3}$	$1.2385x10^{-6}$
8/28/74-1.3	$1.7761x10^{-3}$	$2.4243x10^{-5}$	$7.4857x10^{-7}$

Coefficients for equation 1 for each of the seven samples based on the data contained in Table 1. (Data used for first set of computations)

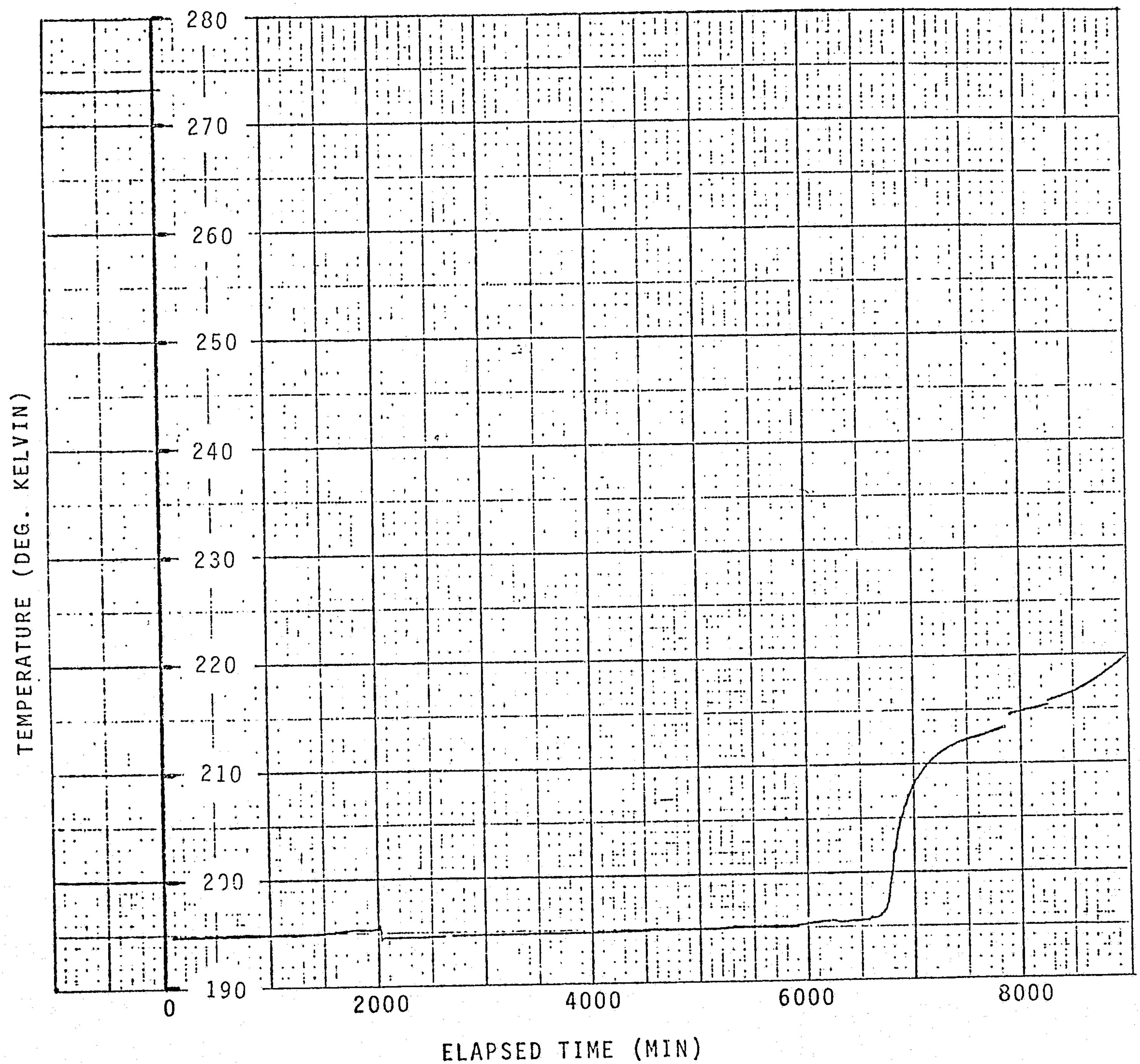

Figure 6. Plot of the temperature of PRT FL-31 as a function of elapsed time.

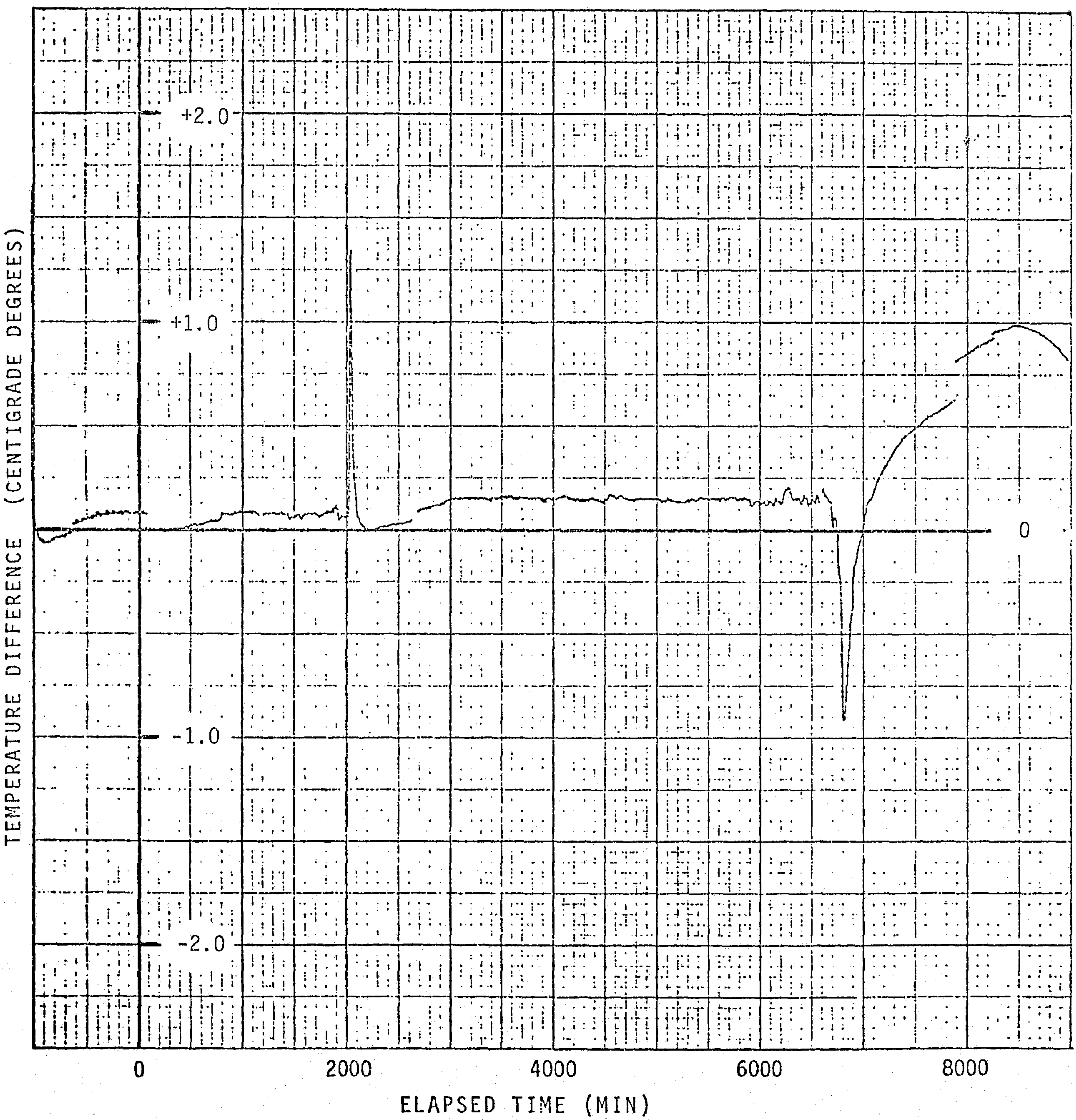

Figure 7. Plot of the difference in temperature between thin film sample 10/28/74-1.3 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 2

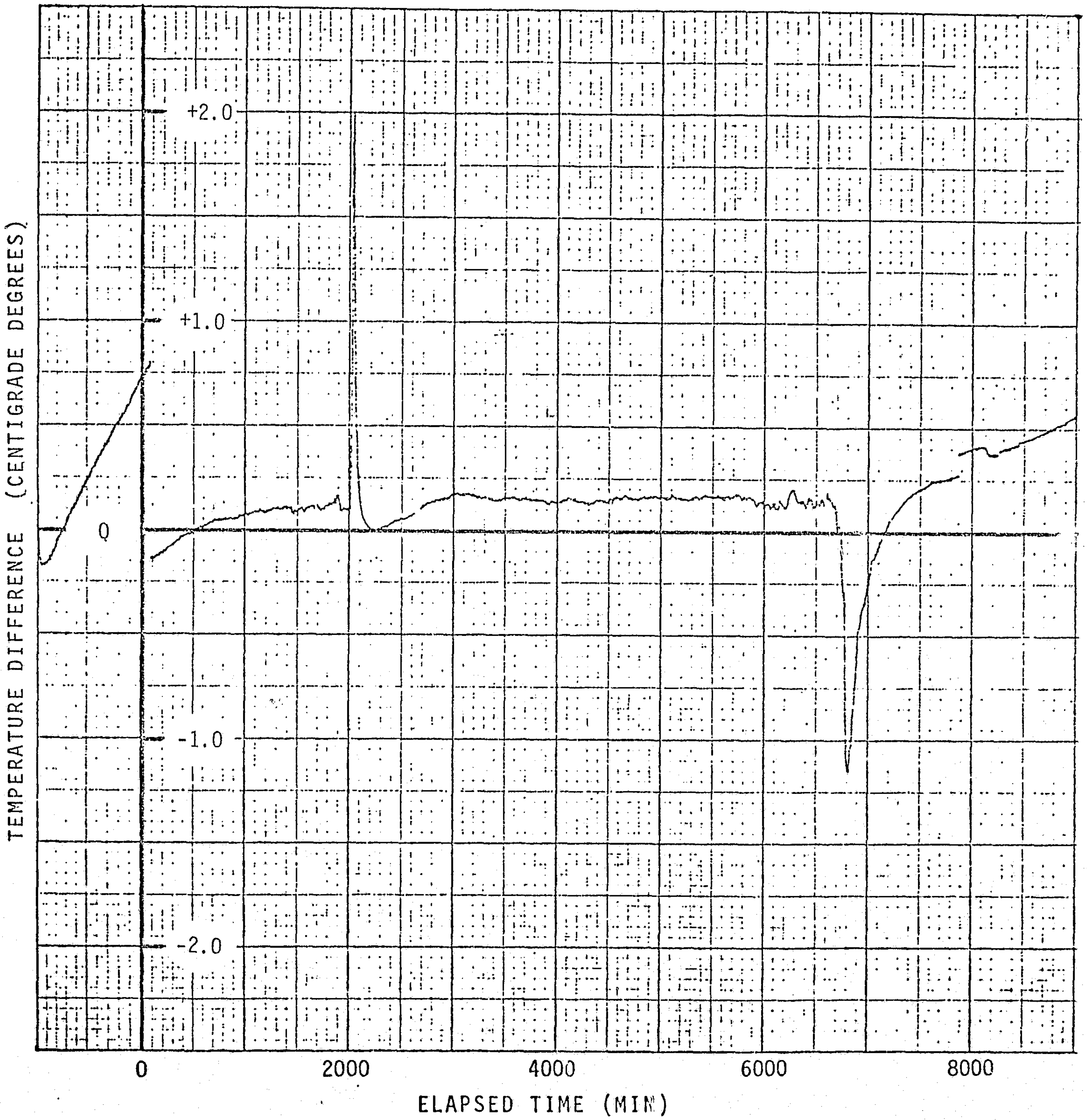

Figure 8. Plot of the difference in temperature between thin film sample 10/27/74-1.3 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 2.

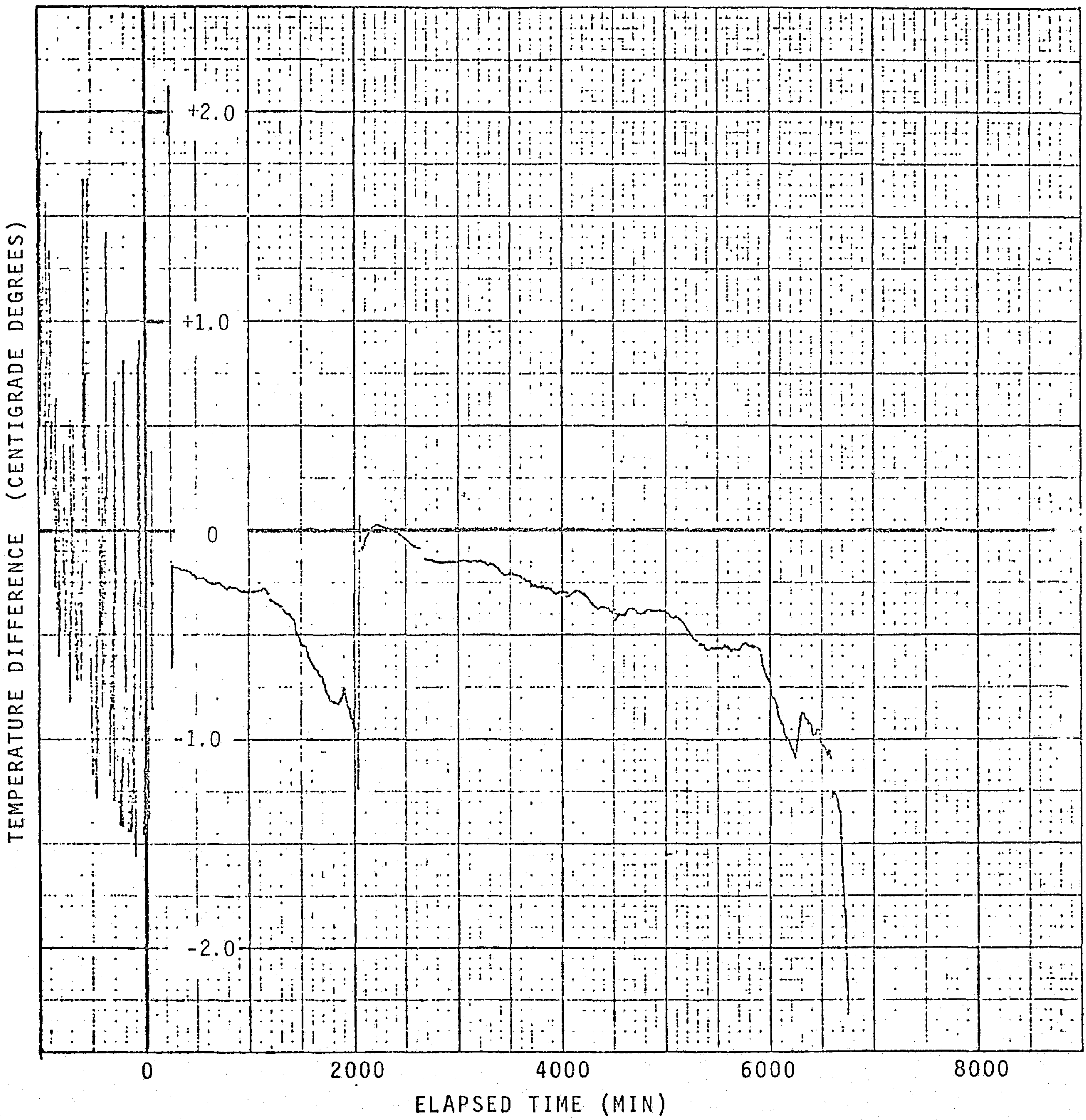

Figure 9. Plot of the difference in temperature between thin film sample 10/28/74-1.2 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 2.

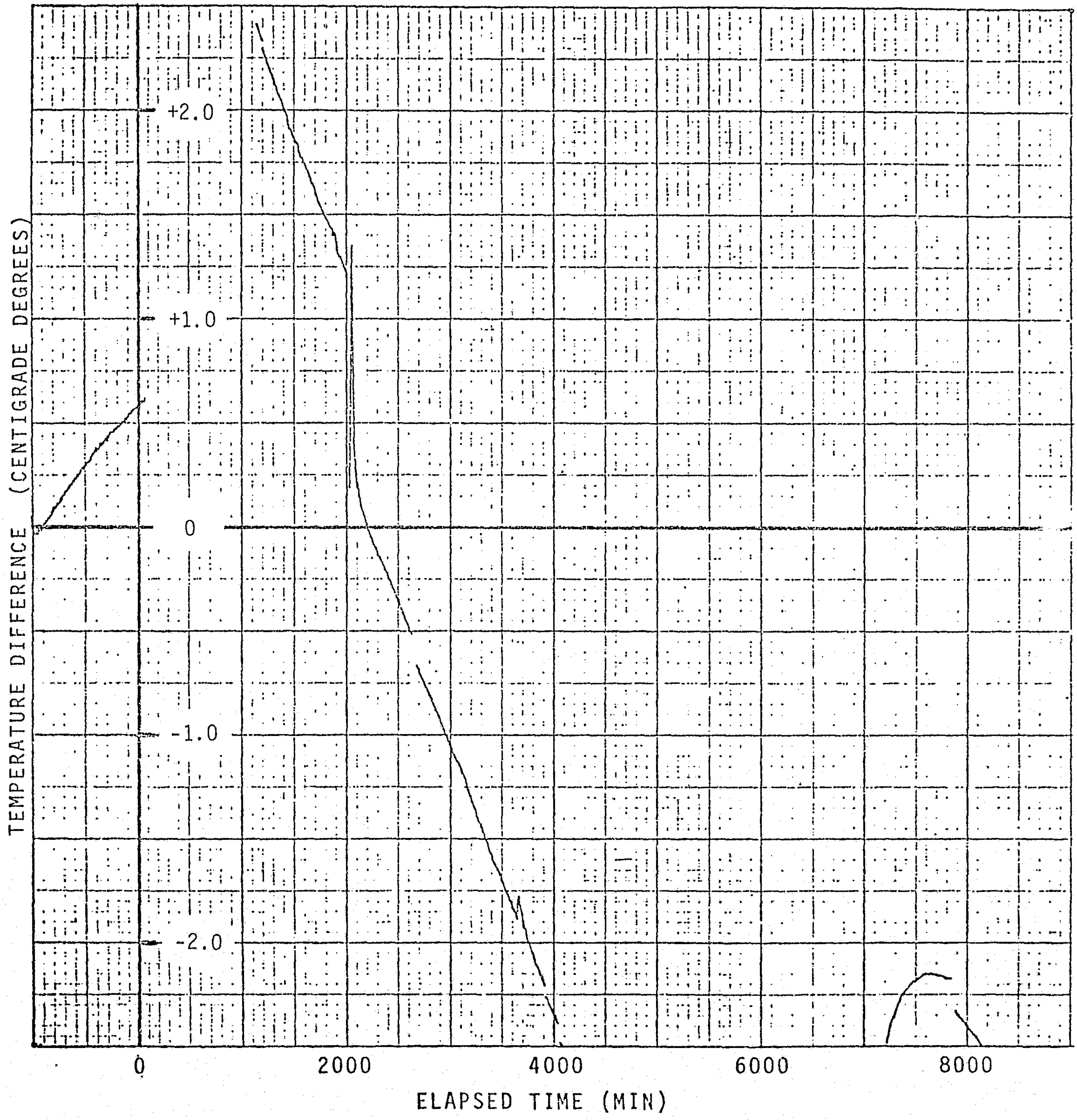

Figure 10. Plot of the difference in temperature between thin film sample 9/17/74-1.3 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 2.

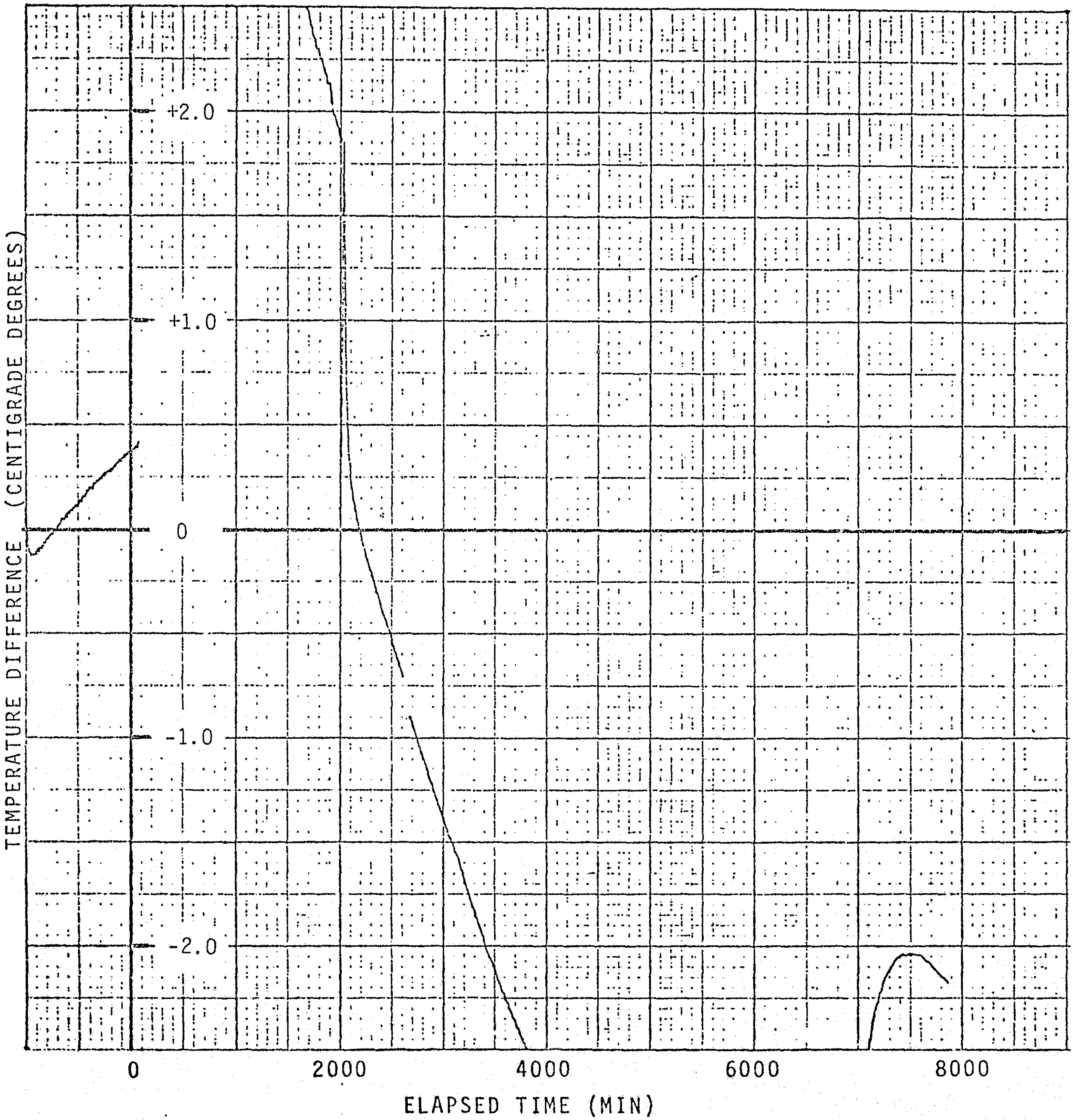

Figure 11. Plot of the difference in temperature between thin film sample 9/17/74-1.2 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 2.

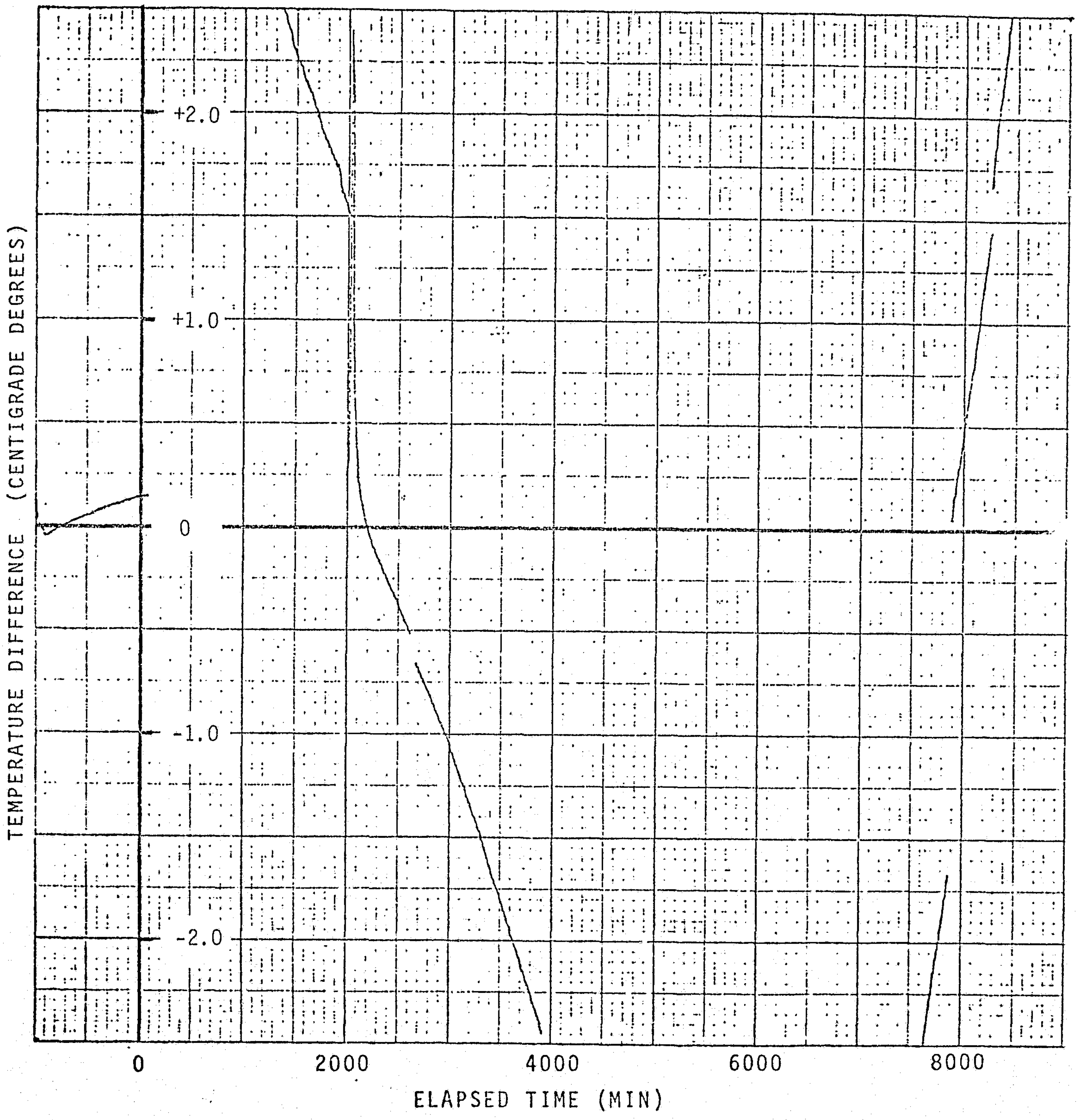

Figure 12. Plot of the difference in temperature between thin film sample 8/28/74-1.3 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 2.

The sample numbers indicated above correspond to the date the sample was deposited. With this amount of elapsed time between fabrication and testing they should have stabilized.

When the samples returned to room temperature following this series of measurements it was noted that their resistance had changed. Another set of measurements were then made at room temperature and at the distilled ice water temperature. The resistance vs. temperature results obtained from this new set of measurements is shown in Table 3 and the corresponding coefficients for eq. 1 are shown in Table 4. In arriving at these new values the temperature of the chamber was allowed to stabilize, in each case, for two days before acquiring the data used for these calculations.

Figures 13, 14, and 15 show the room temperature results obtained for the three samples shown in Fig. 4. Note that, although the temperature range is slightly different, both sets of data include the temperature $19^{o}C$. After the chamber had been allowed to stabilize in the distilled ice water bath, the variations in PRTs FL-31 and FL-51 were less than ±1 count which corresponds to ±0.01 C^{o} over a seven hour period. For the acetone and dry ice calibration point, referring to Figs. 7 and 8 and the data print-out, an extended period of time was selected during which the temperature of the samples appeared to be stable.

Using these new coefficients the data presented in Figs. 7-12 was again plotted. These results are presented in Figs. 16, 17, 18, and 19. Since the earlier data obtained at $273^{o}K$ were inconsistent with these later

TABLE 3

SAMPLE NUMBER	SAMPLE RESISTANCE [OHMS] 273.07°K	292.15°K	194.72°K
9/17/74-1.3	503,450	552,600	6,084,450
10/28/74-1.3	257,350	188,010	4,190,200
9/17/74-1.2	261,000	223,940	6,780,000
10/28/74-1.2	263,800	193,770	4,203,200
10/27/74-1.3	356,250	280,900	2,649,550
8/25/74-1.3	388,300	299,180	6,408,200
8/28/74-1.3	593,650	524,360	8,005,000

Measured resistance of thin film samples at selected calibration temperatures. (data used for second set of computations)

TABLE 4

SAMPLE NUMBER	COEFFICIENTS FOR EQUATION 1 [°K^{-1}] A	B	C
9/17/74-1.3	1.8089×10^{-1}	-1.8907×10^{-2}	3.1373×10^{-5}
10/28/74-1.3	-1.2861×10^{-2}	1.6195×10^{-3}	-1.8892×10^{-6}
9/17/74-1.2	-4.6394×10^{-2}	5.2622×10^{-3}	-8.0276×10^{-6}
10/28/74-1.2	-1.3428×10^{-2}	1.6774×10^{-3}	-1.9784×10^{-6}
10/27/74-1.3	-2.1480×10^{-2}	2.4606×10^{-3}	-3.0220×10^{-6}
8/25/74-1.3	-2.0985×10^{-2}	2.4296×10^{-3}	-3.1062×10^{-6}
8/28/74-1.3	-7.6558×10^{-2}	8.1170×10^{-3}	-1.1785×10^{-5}

Coefficients for equation 1 for each of the seven samples based on the data contained in Table 3. (Data used for second set of computations)

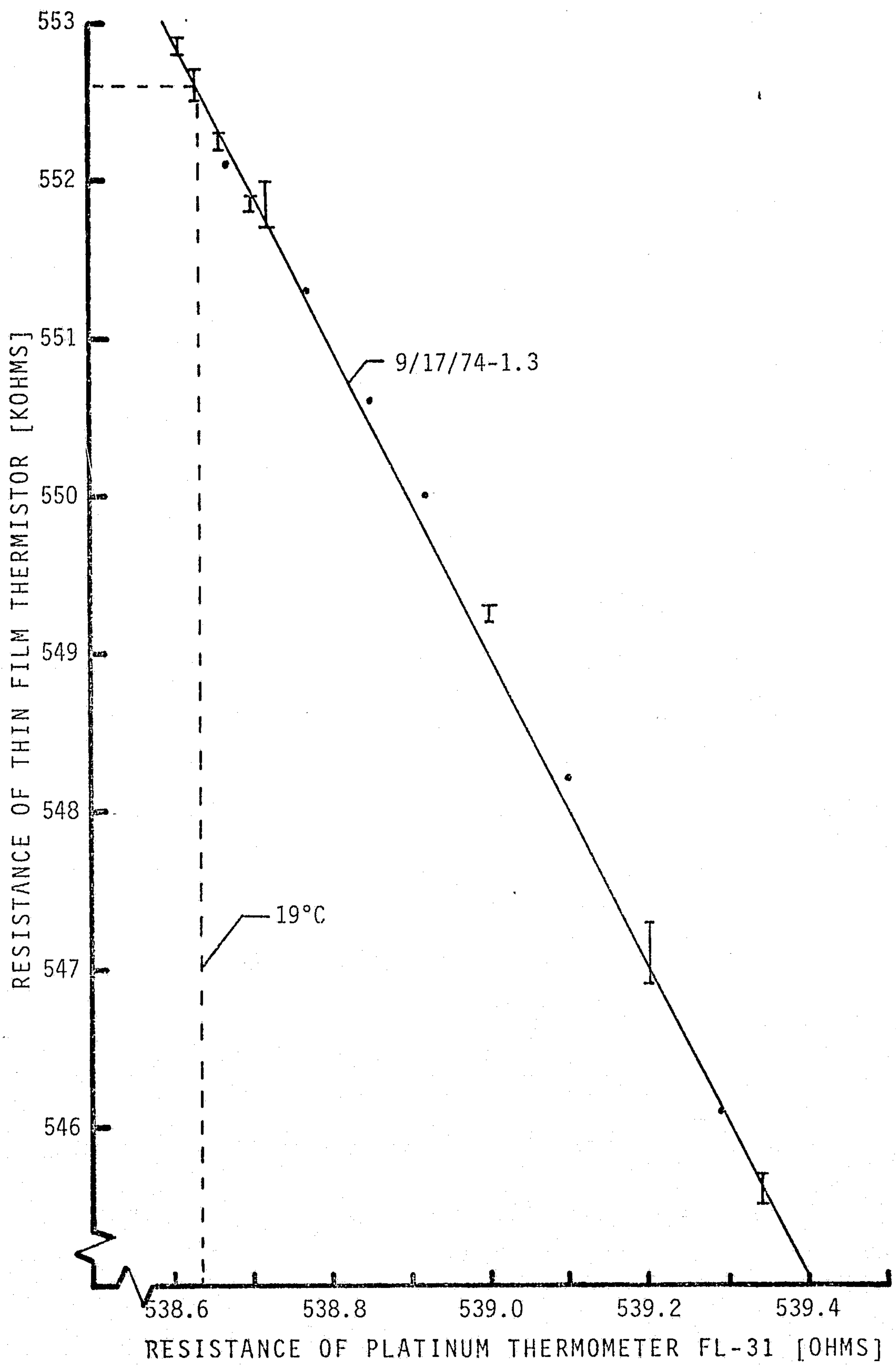

Figure 13. The resistance of thin film thermistor 9/17/74-1.3 as a function of the resistance of PRT FL-31.

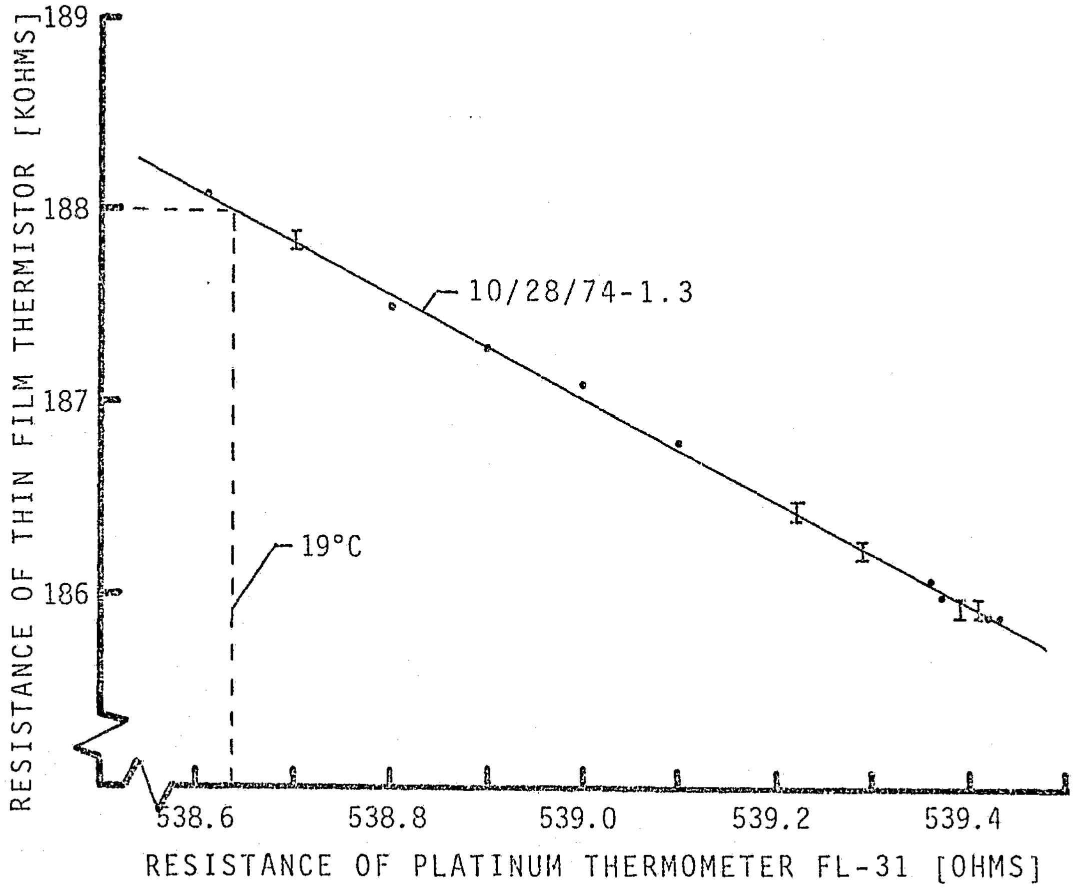

Figure 14. The resistance of thin film thermistor 10/28/74-1.3 as a function of the resistance of PRT FL-31.

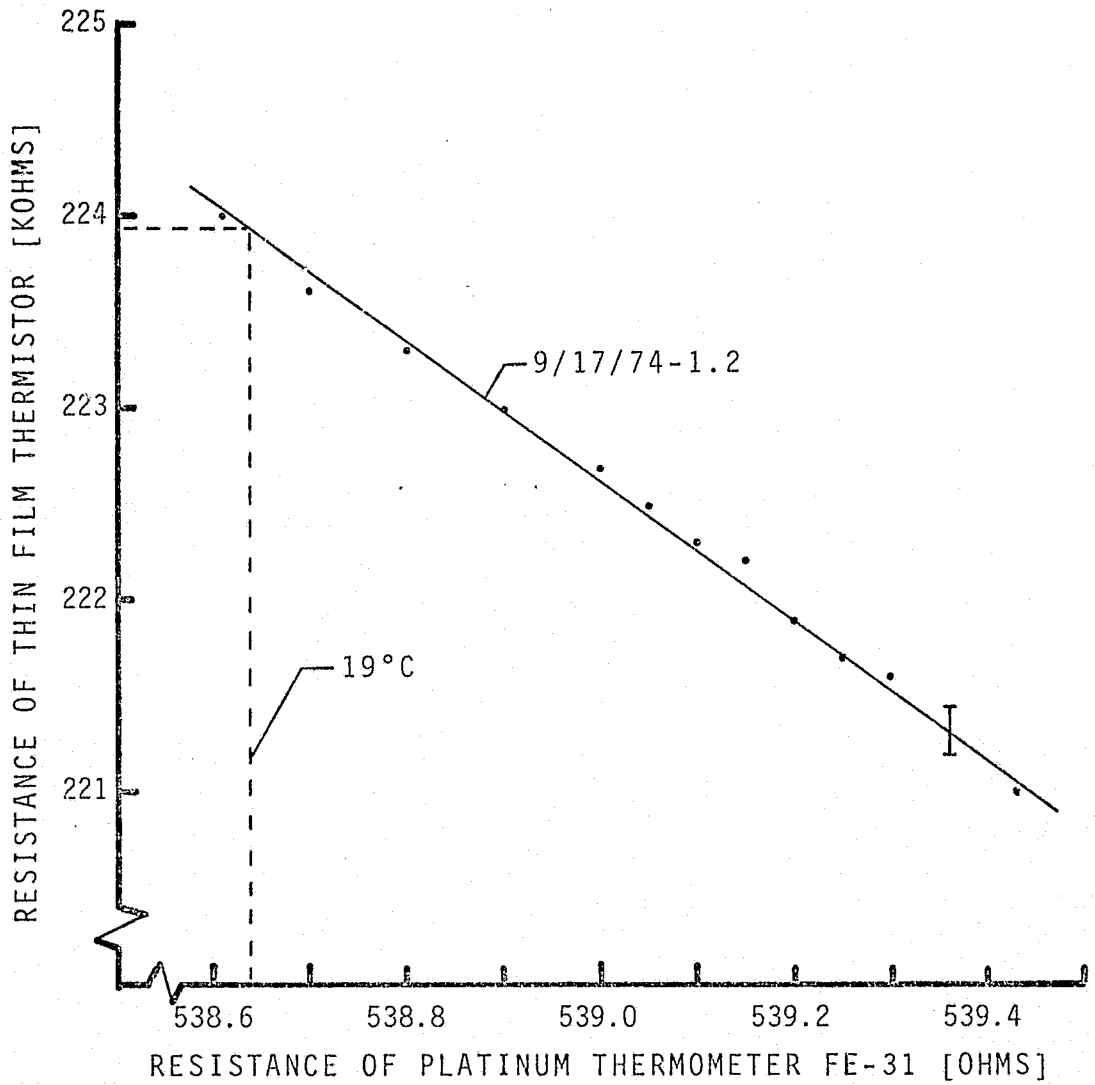

Figure 15. The resistance of thin film thermistor 9/17/74-1.2 as a function of the resistance of PRT FL-31.

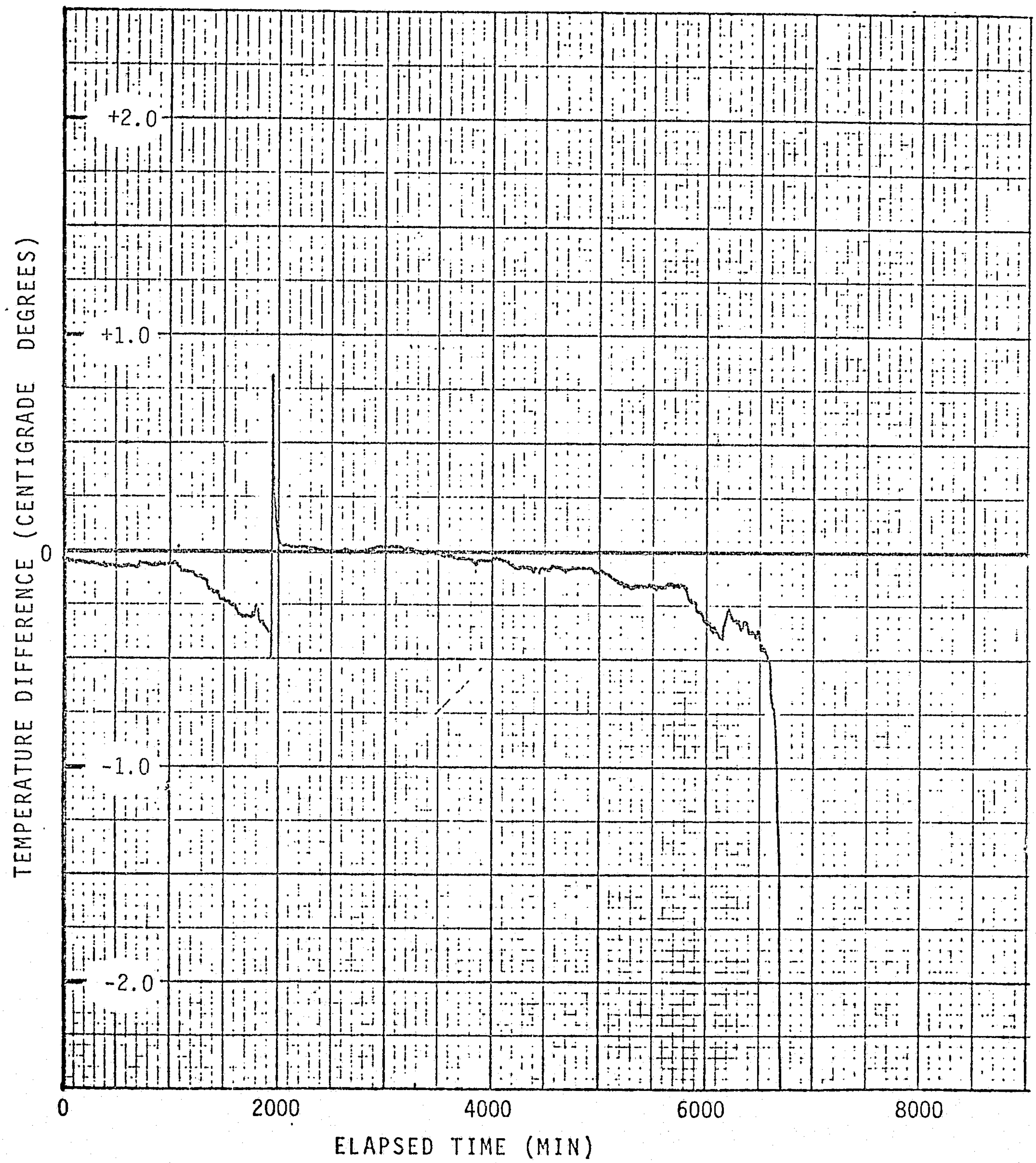

Figure 16. Plot of the difference in temperature between thin film sample 10/28/74-1.3 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 4.

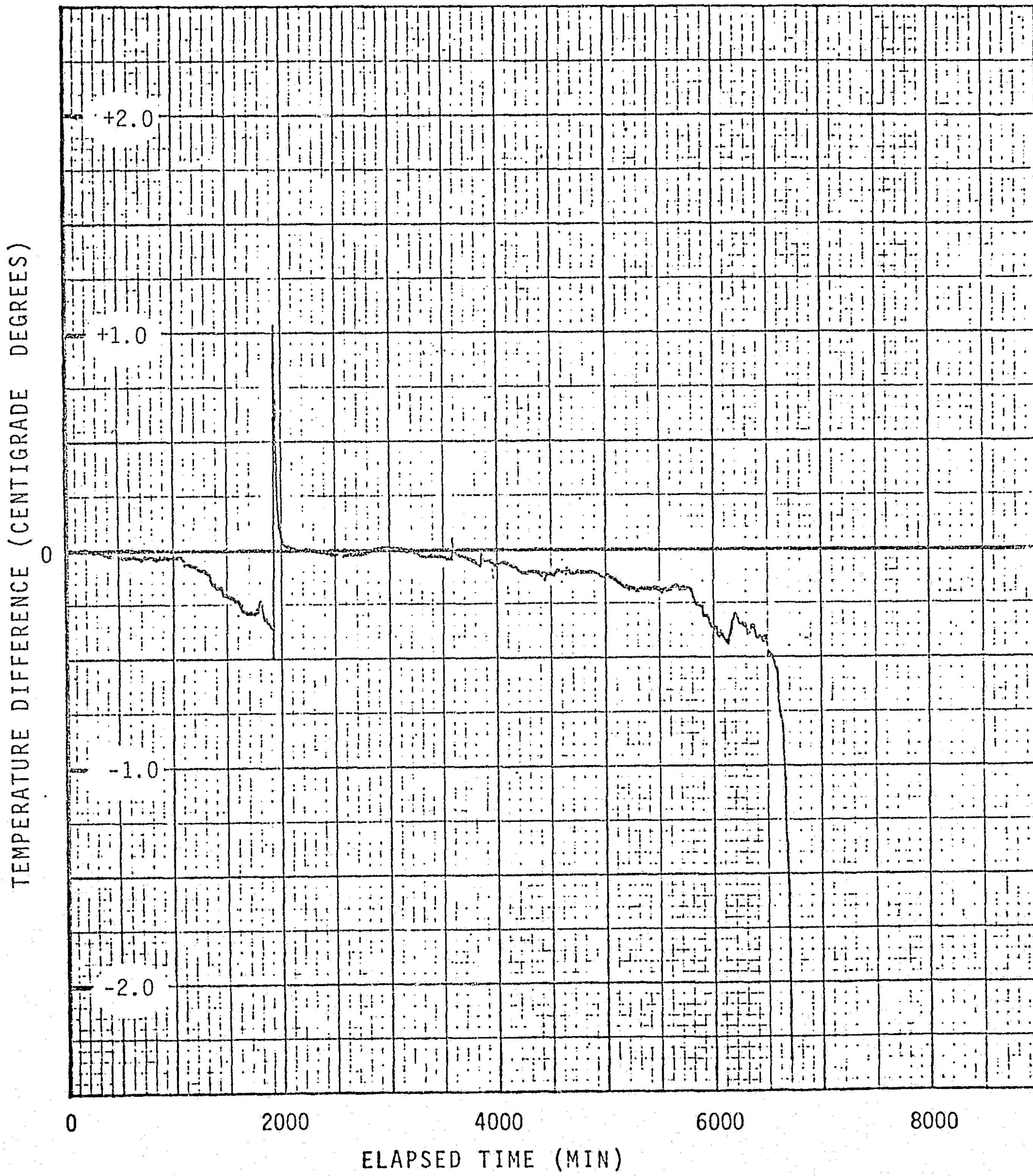

Figure 17. Plot of the difference in temperature between thin film sample 10/28/74-1.2 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 4.

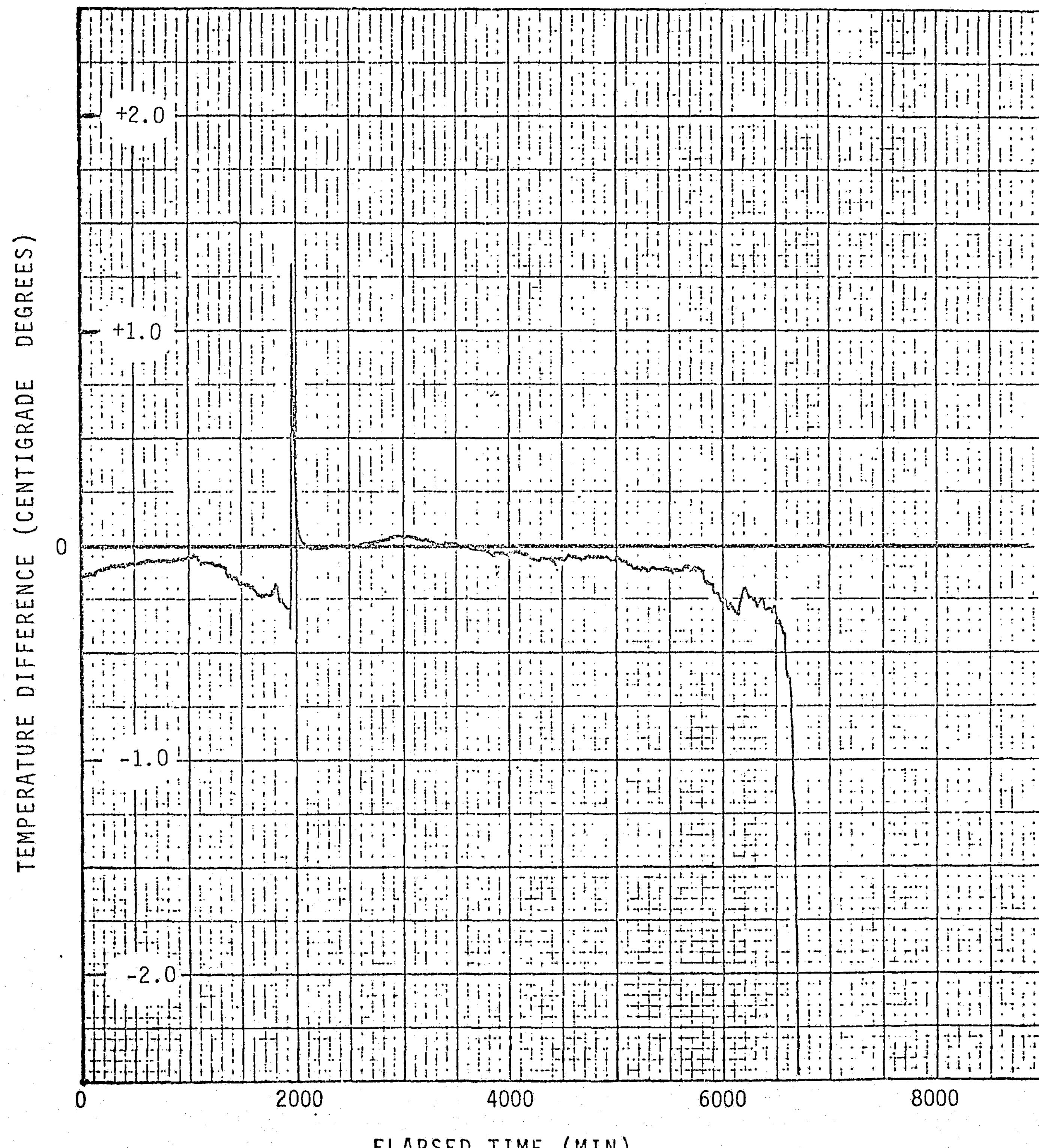

Figure 18. Plot of the difference in temperature between thin film sample 10/27/74-1.3 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 4.

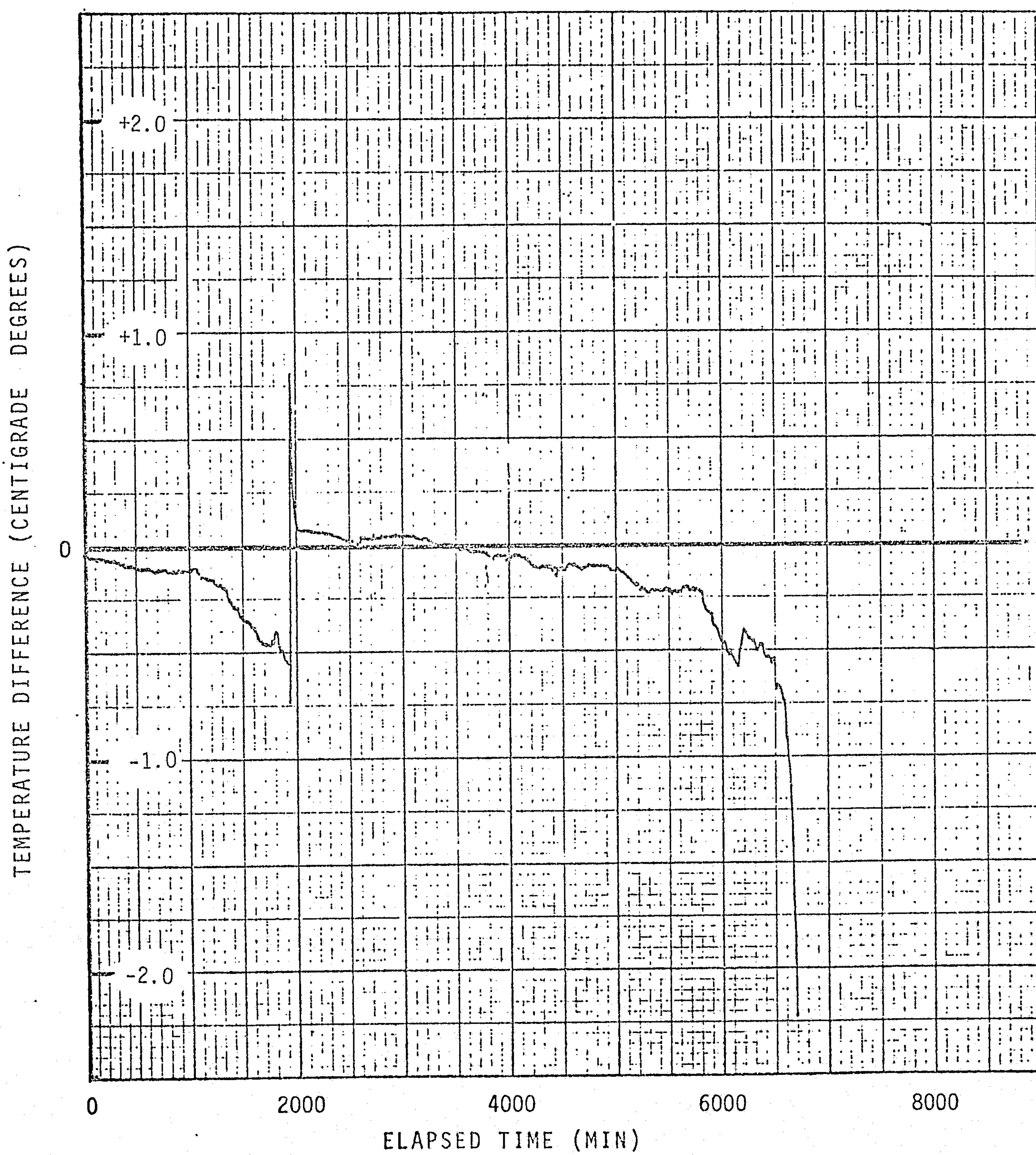

Figure 19. Plot of the difference in temperature between thin film sample 8 /25/74-1.3 and PRT FL-31 as a function of elapsed time. The temperature of the thin film sample was computed using Eq. 1 and data from Table 4.

measurements it was omitted from these last four curves. (Four of the seven samples tested now yielded similar results.) No results are presented for the third group of samples since their characteristics continued to drift and any reasonable comparison was impossible.

SUMMARY

This research effort covered a period of five years. During that period the research furnished some degree of financial support to seven masters candidates and two doctoral candidates. In addition to these graduate students, a number of undergraduate students have benefited from the research either financially or through the use of the facilities. Three technical papers related to the research have been presented at technical meetings and published either in the proceedings of the meeting or in scientific journals. (These papers are listed at the end of this report.) At least one additional publication is anticipated at this time.

Sensors have been fabricated which have characteristics satisfactory for flight. Two difficulties which must be overcome before these devices are satisfactory for extensive use are the extensive time required for fabrication and the lack of uniformity in device characteristics. The first of these difficulties, fabrication time, could probably be solved using commercial facilities designed for high production rates. The second difficulty, uniformity, is characteristic of the entire semiconductor industry. Based on our work we believe that with careful control of the deposition process the majority of the devices fabricated will have satisfactory characteristics. With a proper selection procedure it should be possible to select fabricated samples which possess satisfactory characteristics. In conclusion, if sufficient need exists to warrant mass production of the thin film thermistor it should be possible to produce satisfactory devices at a reasonable price.

PAPERS RESULTING FROM THIS RESEARCH

"A Thin Film Temperature Sensor" - W. D. McLennan, R. T. Ooten, D. S. Bynum, J. L. Palmer, K. N. Pendley, and C. R. Baxter

> Presented at the 21st National Symposium of the American Vacuum Society; Anaheim, California; October 1974.
>
> Published in J. Vac. Sci. Tech., Vol. 12, #1, pp. 71-3, Jan/Feb, 1975.

"Ovonic Switching in Tin Selenide Thin Films" - C. R. Baxter and W. D. McLennan

> Presented at the 21st National Symposium of the American Vacuum Society, Anaheim, California; October 1974
>
> Published in J. Vac. Sci. Tech., Vol. 12, #1, pp.110-3, Jan/Feb, 1975

"A Computer Controlled Procedure for Testing Memory Type Ovonic Switches" - C. R. Baxter, W. D. McLennan, A. R. Atkins, and B. W. Simpson

> Presented at IEEE Southeastcon-75; Charlotte, North Carolina; April 1975 and published in the conference proceedings.

APPENDIX I

A DIGITAL CONTROLLER FOR THIN FILM DEPOSITION

A Dissertation

Presented to

the Faculty of the Graduate School

Tennessee Technological University

In Partial Fulfillment

of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

Engineering

by

Allen Riley Atkins, II

August 1975

AN ABSTRACT OF A DISSERTATION

A DIGITAL CONTROLLER FOR THIN FILM DEPOSITION

Allen Riley Atkins, II

Doctor of Philosophy--Engineering

The need for a precise deposition rate controller is presented in a brief survey given in this dissertation. A digital controller for thin film deposition rate control was designed, fabricated, and tested. The hardware and software presented describes a system capable of thin film deposition rate control of better than .1 Å/sec. Other features the system includes are real time monitoring of the critical parameters, hardcopy output of these parameters, and a statistical analysis of the data taken during the deposition process. The results presented show that the control characteristics of the digital controller appear to exceed those of any other thin film deposition controller on the commercial market.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Dr. William D. McLennan, chairman of the author's Graduate Advisory Committee, for his invaluable assistance and encouragement during this study. Appreciation is also extended to the Physical Electronics Research Group in the College of engineering and to Dr. S. G. Lele, Dr. A. E. Traver, Dr. J. T. Scardina, and Dr. Leland Long, members of the Graduate Advisory Committee, for their contribution and support during this study.

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The author is especially grateful to Mr. Charles Hardesty of NASA at Langley, Vigrinia, for the support given to this effort. Special appreciation is given to the author's wife and children for their support, sacrifices, and understanding during the author's educational efforts.

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LIST OF SYMBOLS

Symbol	
α	(1-confidence level)
Å	Angstrom units (10^{-10} m)
a_1	Adaptive Coefficient
a_2	Adaptive Coefficient
b_1	Adaptive Coefficient
b_2	Adaptive Coefficient
B2	Digital controller software input for velocity multiplier
CF	Controllability factor (Hz/sec)
C_K	Output of deposition process at k-th interval (Hz/sec)
e_K	Error signal to digital control law at k-th interval (Hz/sec)
e	2.7183
f(x)	Normal distribution for given mean and standard deviation
K_1	First rate data point in statistical analysis
K_2	Last rate data point in statistical analysis
M1	Proportionality contact to convert voltage--Hz/sec or voltage--Angstrom/sec (Hz/sec-volts, Å/sec-volts)
M_K	Controller output at k-th interval
μ	Mean value of a distribution function
μ_u	Upper confidence limit for true mean value
μ_L	Lower confidence limit for true mean value
μ_R	Standard deviation of the rate variable
π	3.14159
n	Number of sample matrix points

Symbol	
r_K	Desired rate of deposition (Hz/sec)
$\overline{R}$	Mean rate (Hz/sec)
R_i	Rate value at the i-th interval (Hz/sec)
R_F	Reproducibility factor (Hz/sec)
R_F	Final rise setting for digital controller
R_I	Initial rise setting for digital controller
R_{12}	Mean rate between interval K_1, K_2
S	Estimated standard deviation of a distribution about the mean
$S_{\overline{R}}$	Standard deviation about mean $\overline{R}$
$S_{\overline{SD}}$	Standard deviation about the mean $\overline{SD}$
$\overline{SD}$	Mean of a series of standard deviation values
σ	Standard deviation of a distribution about the mean
$t_{\alpha/2}$	Student t-distribution for confidence level of $\alpha/2$
T_R	Rise time
T_S	Soak time
V_i	Voltage measurement at the i-th interval
$\overline{x}$	Estimated mean of a normal distribution

Chapter 1

INTRODUCTION

In the area of thin film device fabrication, parameters such as rate of material deposition, film thickness, and substrate temperature influence the properties of the film device. Some researchers [1, 2] have concluded that the rate of deposition and the thickness of the film are probably the more important of the various parameters.

Precise control of the deposition parameters has become a must if the reproducibility of a thin film device with defined characteristics is to be expected. If valid data are to be gathered on the effects that these parameters have on the characteristics of the devices fabricated, then precise control is needed to insure that the variations in the characteristics can be correlated with the deposition parameters.

Electronic equipment that offers control of these two parameters has been available commercially for several years. Probably the first thickness measuring technique was described by Turner [3] and Butuzan [4]. It consisted of a bridge circuit to measure the resistance of the material as it was being deposited between two electrodes. Using this method, devices having desired resistances and thus thickness could readily be obtained.

Weissman and Hirsch [5] later developed a technique based on the torque produced by a moment arm being struck by evaporated particles to measure a signal which was proportional to the rate of deposition.

By integrating the "rate" signal, the thickness of the film could be obtained. The momentum associated with the particles of evaporant striking the surface at the end of a moment arm was measured and amplified to give a crude but novel method of obtaining the deposition rate.

In 1963, Brownell, McLennan, Ramey and White [6] introduced an automatic thin film vacuum deposition system. It consisted of a sub-miniature ionization gauge which was placed in the path of the evaporating material and measured the density of particles passing through the gauge, and thus, the rate of deposition. The signal from the ionization gauge, being proportional to the deposition rate, was used as a feedback signal for automatic rate control.

Concurrent with the introduction of the ionization gauge as a method for measuring and controlling deposition rate and film thickness, Lins and Oberg [7] developed the quartz-crystal monitoring system to accomplish the same function. Their system consisted of a thin quartz-crystal mounted such that one face of the crystal was exposed to the evaporation source. Connected in an oscillator circuit, the crystal's resonant frequency decreased as the thickness of the material deposited on the exposed face increased. By subtracting this crystal frequency from that of an oscillator of fixed frequency, a variable frequency signal directly proportional to the thickness of the film was realized. Compactness, accuracy, and response speed made the quartz-crystal monitor the state of the art method for monitoring the rate and thickness parameters. Lawson [8], using a quartz-crystal monitoring system, was able to measure film thickness during deposition to an accuracy of one percent.

Even though the quartz-crystal monitoring system offered many advantages over other methods of monitoring and control, it too had some disadvantages [9]. The primary problem, illustrated in Fig. 1.1, was a sudden frequency shift of the quartz-crystal during deposition. At points A and B, one can see that the frequency output from the crystal took an abrupt change and, in both cases, generated an abrupt increased rate indication which in turn caused an abrupt change in the controlling voltage to the electron gun.

The cause for these frequency shifts has been attributed to combinations of thermal, mechanical and/or electrical shock. Since the thermal effects appear to influence the frequency stability more than the other effects, various techniques have been suggested to curtail this effect. Thermally shielding the outer casing of the sensor was a possible solution suggested by Riegert [10] to ease the thermal effects. Other suggestions which have been made include mounting the crystal on blocks with high thermal inertia, i.e., heat sinking, water cooling the sensor walls or placing optical baffles to cut down on radiation heating. Even with the use of thermal shielding and the other techniques, the problem of unexpected frequency shifts still exists.

Until the introduction of the computer, an accurate rate controller capable of handling these frequency shifts appeared unrealizable. In 1972, Effron, Farrow, and Thitcomb [11] of IBM produced a system consisting of a vacuum deposition unit controlled by a large computer. With their system a reproducible copper-tin metallic film could be achieved, along with the added capability of real time data monitoring, storage, retrieval, and computation. Although statistical information indicated how well the computer controlled both the thickness and the

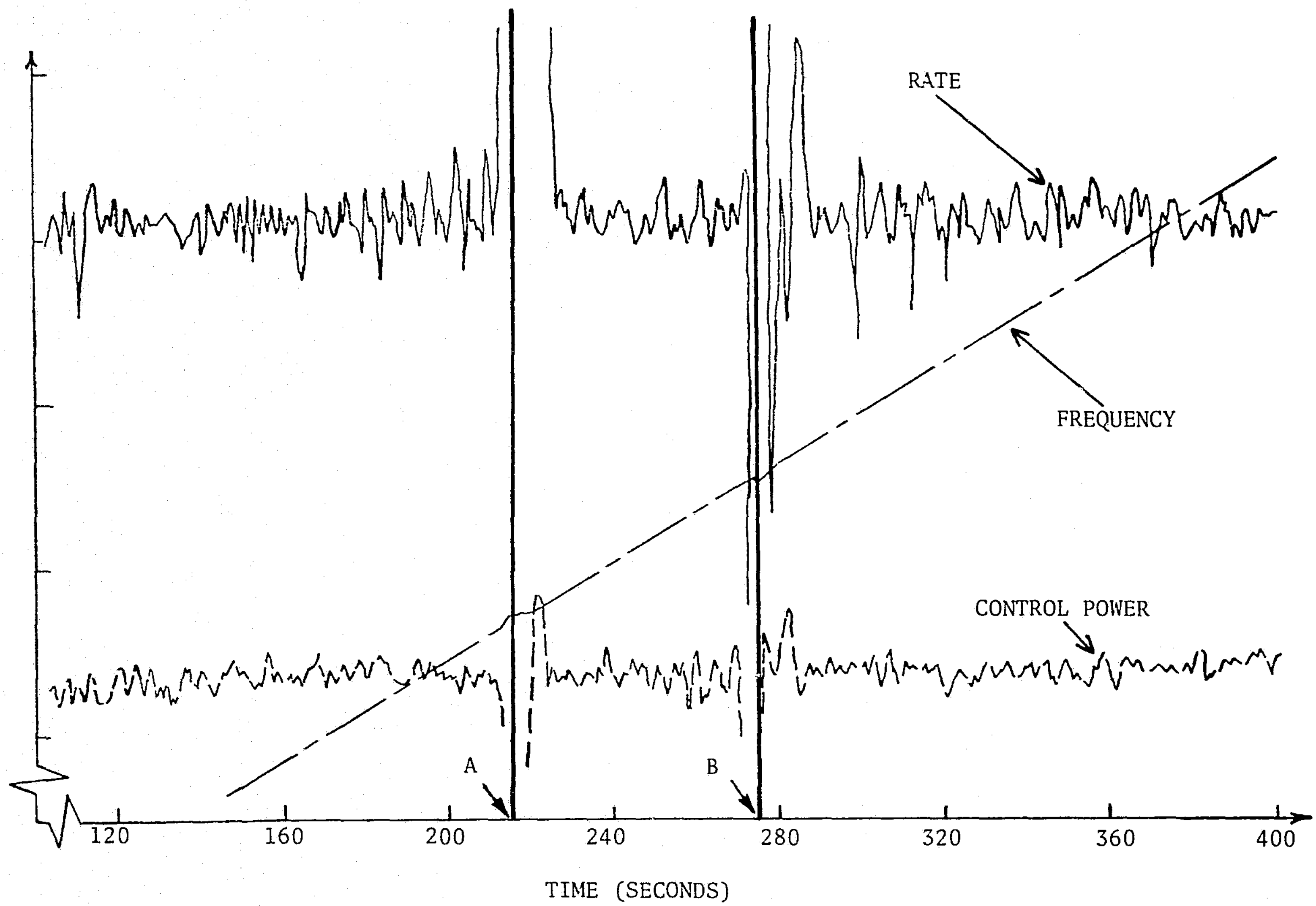


Figure 1.1. Analog Response to Crystal Snap

average deposition rate, there was no indication as to the uniformity of the rate control (i.e., how much standard deviation from the average could be expected). Also, no effort was made to use the system for controlling the deposition of materials other than metals. This is important since semiconducting materials are far more sensitive to variation in the deposition parameters. Techniques utilizing the computer to alleviate the unexpected frequency shift associated with the crystal monitor proved to greatly enhance the monitoring technique. Therefore, the possibility of using the computer to monitor and control thin film deposition parameters appeared to be feasible.

At the same time the IBM system was being developed, Centner and Wilson [12] investigated the possibility, from a theoretical and economical standpoint, of using a digital processor (mini-computer) to achieve the same results. They suggested the primary advantage of using the digital processor as compared to either a large machine or an analog unit was the cost factor. The cost advantage that most digital processors have in comparison to digital machines is obvious, but their cost advantage over an analog deposition controller is not readily evident. The cost of an analog control unit including sensor heads and the accessories necessary to control the rate of deposition, film thickness, and shutter operations can be purchased at a cost equal to or less than the cost of a digital processor and the associated hardware necessary to accomplish the equivalent function. If, however, additional hardware were added to the analog system to allow monitoring, data storage, and retrieval, it would cause the analog system cost to far exceed the equivalent computer system.

Centner and Wilson concluded that another possible advantage the digital processor system offered was that the system would be much more flexible than an analog system. Not only would monitoring and control be possible, but other functions such as data manipulation, statistical analysis, mathematical problems, and other services normally performed by a computing system would be available by changing only the software of the machine. Thus, a greater degree of flexibility could be achieved by using the digital processor to control and monitor the deposition parameters such as deposition rate and film thickness. Also, this approach appears to have advantages over an analog control device if the control achieved by the digital processing system equals or exceeds the control of the analog system.

Figure 1.2 shows a model of the vacuum deposition unit interfaced with an analog control unit, presently in use at Tennessee Technological University. The system shown achieves deposition rate control by mixing the signal from the quartz-crystal sensor with an adjustable frequency oscillator to obtain a low frequency signal directly proportional to the thickness of the material being deposited. This signal is converted to a DC voltage level which can be compared to a voltage level representing the desired film thickness. The difference signal can be used to control the termination of the deposition. By differentiating the DC voltage level with respect to time, a signal proportional to the deposition rate can be obtained and compared to a desired deposition rate. The difference between the two rate signals is then used to control a SCR power controller which supplies power to an electron gun. The electron gun, in turn, supplies energy to the evaporant, causing it to evaporate.

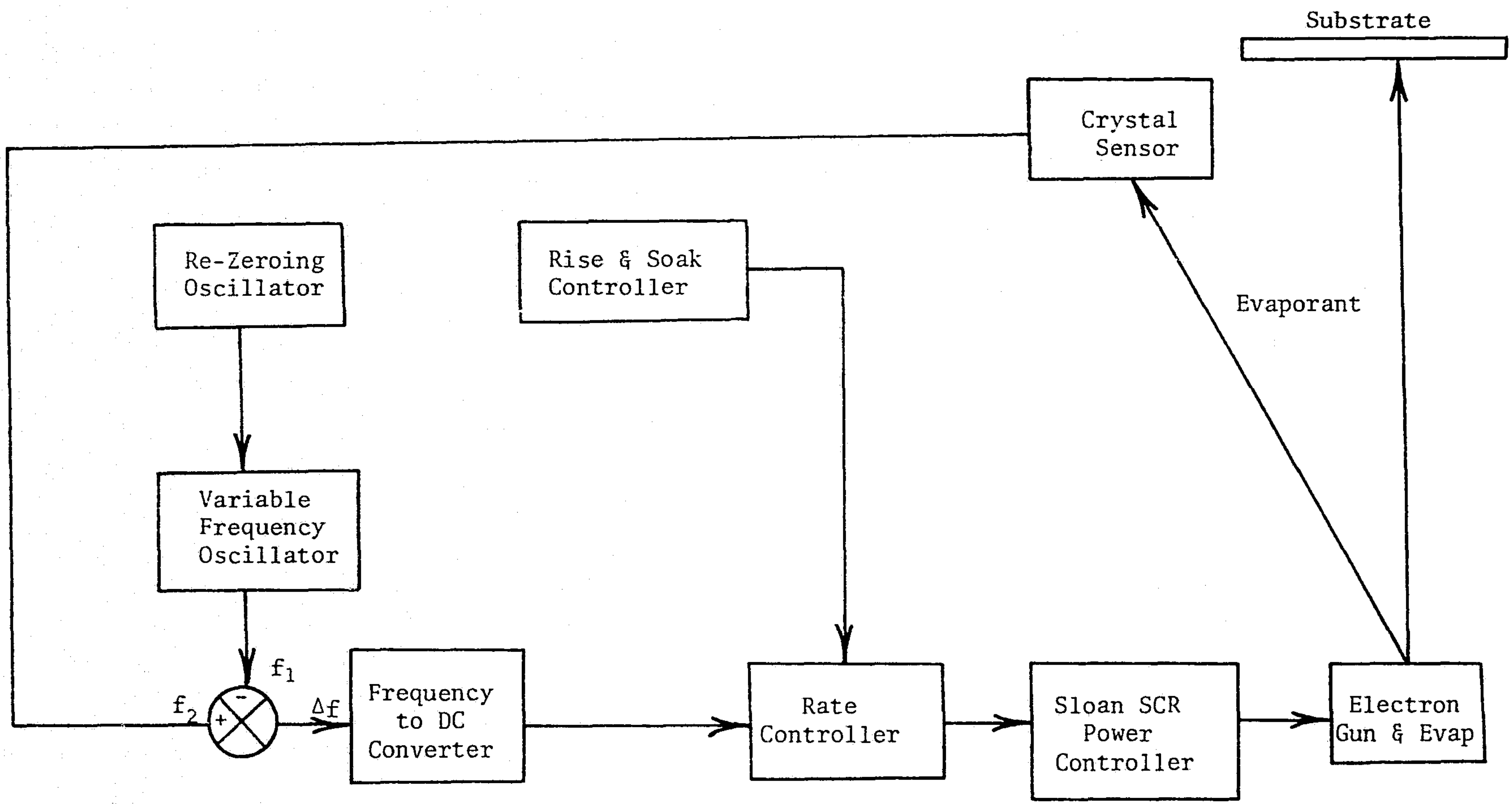


Figure 1.2. Analog Deposition Processor

Thus, a complete feedback system using analog components controls the deposition rate and film thickness.

This dissertation establishes the design criteria for a digital system which will replace parts of the analog system. The hardware and software requirements to perform the task are also defined. Finally, a series of digitally controlled depositions have been made for a comparative analysis with the analog controller. The results of the analysis will illustrate that the digital controller offers many advantages over the analog controller.

Chapter 2

SYSTEM DESCRIPTION

This chapter contains a discussion of the hardware used to initially monitor and ultimately control the deposition process. Each major system, the Analog, the Analog/Digital, and the Digital Control Unit depicted within the block diagram of Fig. 2.1 will be discussed. Only the Analog System existed prior to the undertaking of this research effort. The remaining major systems were designed and integrated to develop the monitoring and deposition controlling system to be discussed. The portion of the figure encompassed by the dashed line is used to monitor the parameters which are set by the analog controller while the entire figure illustrated all components needed to both monitor the deposition and to digitally control the process.

ANALOG SYSTEM

The analog system is illustrated in Fig. 2.2. The components are the SCR Power Controller, Power Transformer, Vacuum Chamber, Electron Gun, Material Crucible, Crystal Detector, and the Analog Rate Controller. Beginning with the SCR Power Controller and following the path of the process, the components of the closed loop control system can be defined. The SCR Power Controller acts as a regulator controlling the power signal. That is, the conductive or "on" portion of the power cycle is controlled by the input signal to the SCR Power Controller.

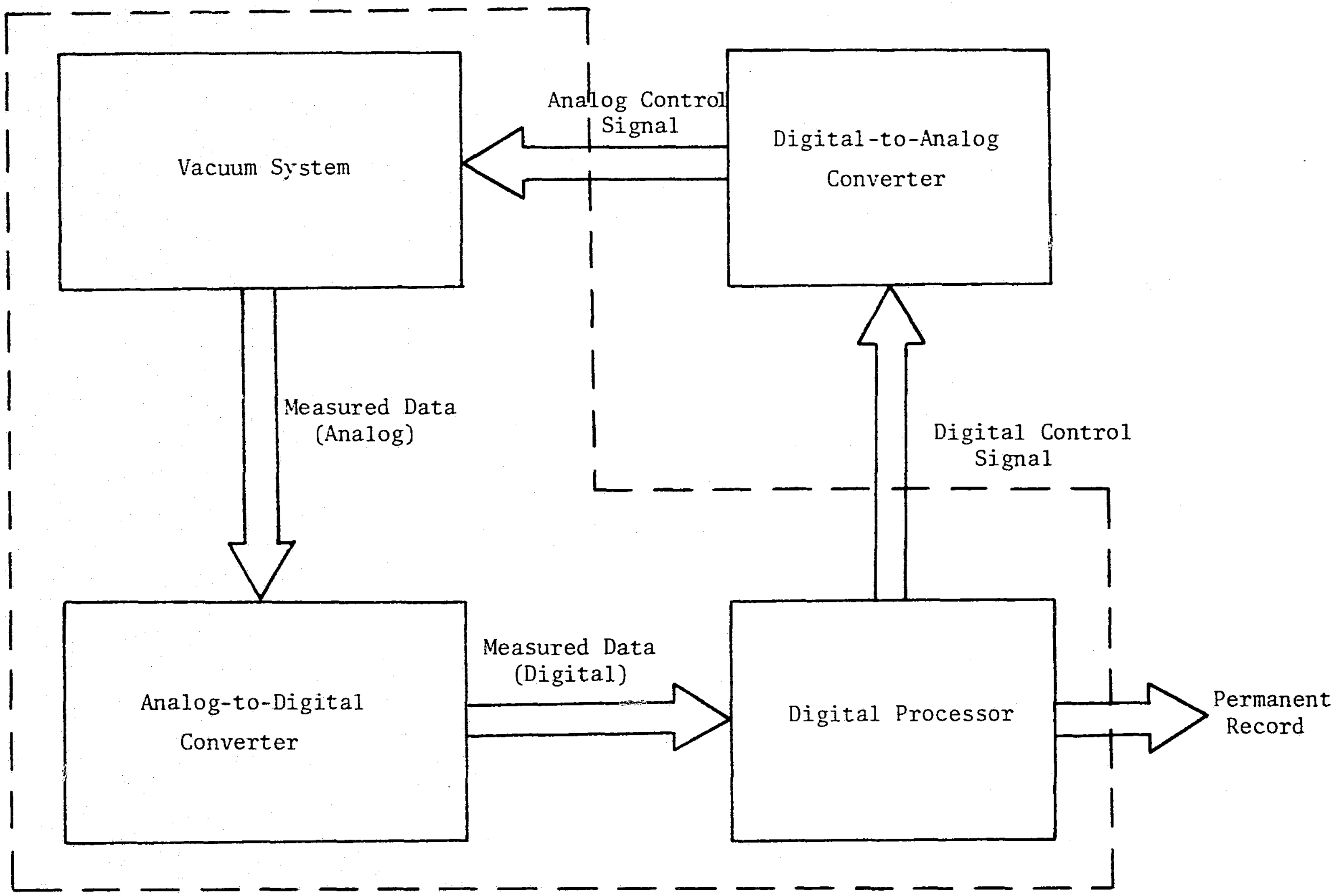


Figure 2.1. Deposition and Monitoring System

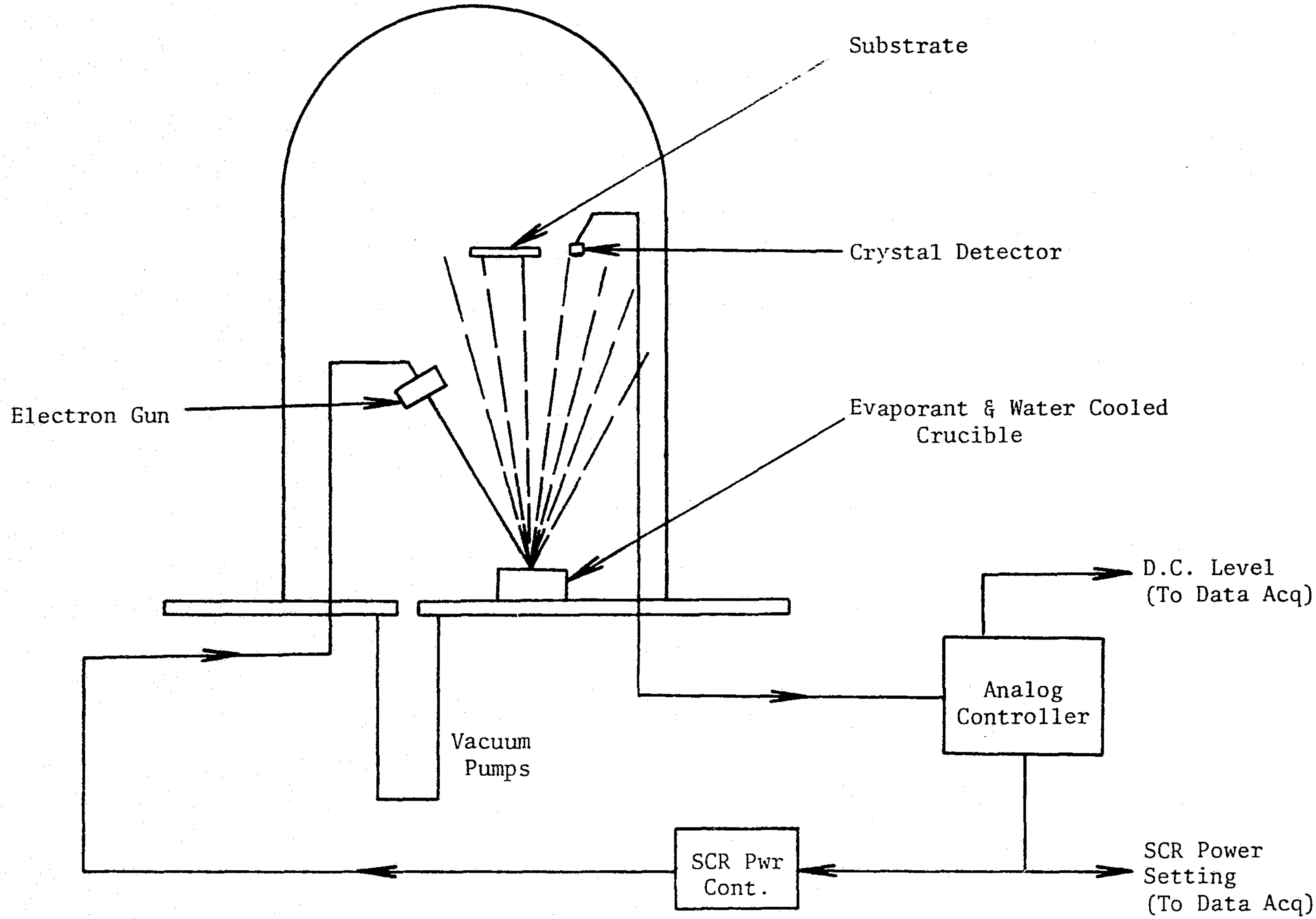


Figure 2.2. Vacuum System

Figure 2.3 illustrates the SCR Power Controller and associated circuitry. The power transformer transforms the 208 volts (AC primary voltage) to an 11 Kilovolt DC output which is superimposed on the AC signal applied to the filament of the electron gun in the vacuum chamber.

The next subsystem to consider is the electron gun. It is capable of delivering up to 6 Kilowatts of power to a water cooled crucible filled with the evaporant. The power supplied to the crucible results when the electrons are emitted from the tungsten filament and accelerated through the 11 Kilovolt potential difference between the filament and the grounded hearth. The gain in kinetic energy is transformed to thermal energy when the electrons strike the deposition material in the crucible. Utilizing the electrostatic fields generated by the high electric potential and the circular geometry of the electron gun, the stream of electrons boiled off the filament is focused to a narrow beam. Once through the electrostatic lens, the beam of electrons experiences very little diffusion due to collisions with other particles within the vacuum chamber. Consequently, the mean free path of the electrons is long. This means the beam power is concentrated within a small region of the crucible.

The high velocity electrons impinging on the evaporant contained in the water cooled crucible are illustrated in Fig. 2.2. The evaporant molecules gain enough energy from the beam to escape the internal bonding forces and evaporate. Most of the evaporant molecules travel in a straight line until they strike a "cool" surface where adhesion with the surface occurs. Thus, adhesion can take place on any surface that is in direct line of sight from the surface of the material being evaporated. Two such surfaces are the substrate on which the thin

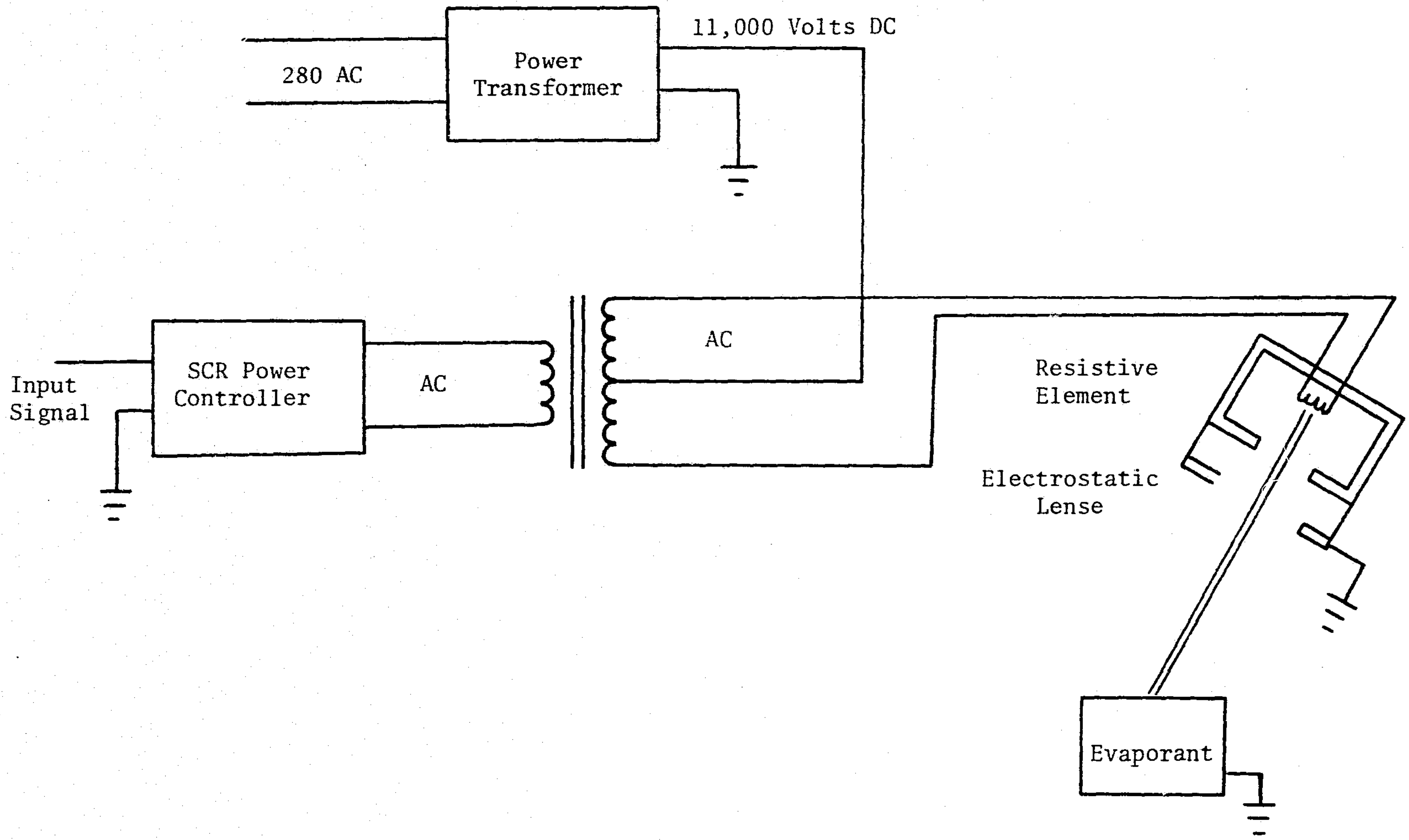


Figure 2.3. Electron Gun Control Diagram

film device is being fabricated and the face of the quartz-crystal monitor.

This evaporation process can be shown to be influenced by two prime factors. The first and probably the most influential is the surrounding, or background pressure, within the vacuum chamber. The higher the background pressure the more energy required to produce a given deposition rate since the mean free path of a molecule is proportional to the background pressure. The second factor that can be shown to have an influence on the evaporation process is the conductive heat transfer coefficient of the evaporant. A material that has a high conductivity coefficient, such as silver, will transfer a large amount of received energy through the material and into the water cooled crucible; while a material with a lower conductivity coefficient, such as the semiconductor material, tin selenide, will not transfer as much of the received energy to the crucible and thus less energy is needed to achieve a given deposition rate.

As indicated, two surfaces which become coated with the evaporant during the deposition process are the substrate and the crystal detector. The crystal detector has the role of a transducer. It transforms the presence of a given mass deposited upon the face of a quartz-crystal into an electrical signal which is readily detectable and satisfactory for processing. As the material is deposited upon the crystal, the resonant frequency of the crystal decreases. Thus, a measurable signal which is proportional to the material deposited is obtained.

The crystal utilized within the system has a resonant frequency near 5 MHz. By mixing this signal with a 5 MHz reference signal, a low frequency difference signal can be obtained which is proportional to the thickness of the mass on the detector face. Figure 2.1 illustrates the next step in the control process which involves the conversion of the frequency signal into a DC signal. In completing the deposition process loop, the DC signal is coupled through a differentiator to obtain a signal proportional to the rate of change of the DC signal. Both signals, the DC voltage corresponding to the thickness indication and the rate of change of the DC level, are coupled to a pair of analog meters to give a real time indication of their variation during the deposition process. The deposition rate signal is compared with a reference signal and the difference is used to drive the SCR Power Controller in order to obtain the desired deposition rate.

As indicated in Chapter 1, there are some disadvantages associated with the analog rate controller. These include crystal snap, noisy differentiation of the DC signal, long settling time, high rate overshoots, inaccurate meter indications, and lack of permanent records of the deposition parameters. The limitation on the maximum time the system allocates to the rise time and the soak time is another disadvantage. The rise time refers to the time required to linearly raise the SCR Power Controller's output to a given setting while the soak time refers to the time this setting is sustained by the system. This limitation becomes an important factor for some materials such as tin selenide which requires a long rise time and platinum which requires a long soak time for outgassing.

This section has described the analog deposition system. Limitations associated with various subsystems have been discussed along with the effects the limitations can have on the deposition process.

This presentation will serve as a basis for discussing the analog-digital system.

ANALOG-DIGITAL SYSTEMS

This section of the chapter will discuss the hardware involved in converting the DC signal from the frequency to DC converter into a digital signal which can be sensed by the Digital Control Unit (DCU) an. the subsequent generation of a control signal to be used for controlling the SCR power supply. The first half of this process requires an analog-to-digital (A/D) signal conversion and is referred to as the monitoring process. The second half requires both a digital-to-analog (D/A) and an A/D signal conversion and is referred to as the controlling process.

Since the A/D converter is required in both the monitoring and controlling processes, it will be discussed first. To perform this conversion, a Hewlett Packard Model 2012A Data Acquisition Unit was used in conjunction with control signals from the DCU. As illustrated in Fig. 2.4, the data acquisition unit is composed of two distinct units, a crossbar scanner and a digital multi-meter (DMM). The 600 channel crossbar scanner is used to select the desired analog data signal to be converted. Other signals, including the DC signal from the vacuum system, are available at the crossbar scanner and can be measured by the system. When controlled by the DCU, the crossbar scanner can be commanded to step through data channels in any desired sequence.

The chosen signal is routed to the DMM where it is converted to a digital signal that can be displayed on the front panel and is simultaneously routed to the DCU. The DMM is capable of interpreting

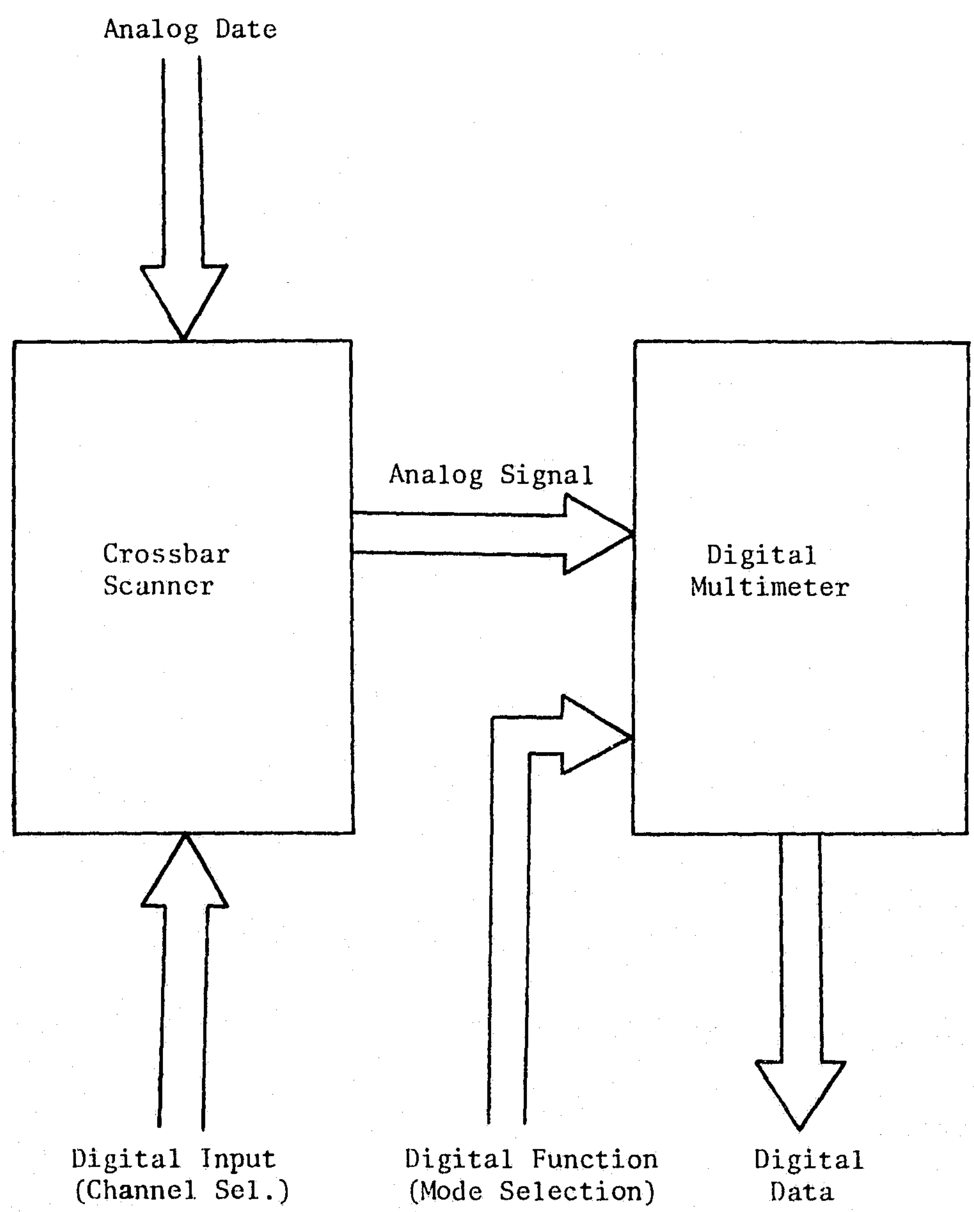


Figure 2.4. Analog-to-Digital Converter

the analog signal as a voltage, a resistance, or a frequency signal depending on the command from the DCU.

One might question the conversion of the crystal signal to a DC signal when the DMM has the capability of frequency measurements. The primary concern is speed. To convert an analog sinusoidal signal to a digital signal, the DMM requires a steady state analog signal for a one second measurement interval in order to reduce the measurement error. Two problems are associated with direct frequency measurement, the frequency changes during the measuring interval and the excessive time required for a measurement. Trying to control a deposition process at a constant rate of 10 Hz/sec frequency shift would generate an invalid digital signal. With reference to the second problem, the measurement interval, the digital control process requires an input signal every second. However, a full second is required for the measurement and additional time is required to transfer the data and commands.

To circumvent the problems associated with the frequency measurement techniques, the linear conversion of the frequency signal to a DC signal offers a plausible solution. The DMM is capable of taking a voltage measurement in approximately 50 milliseconds. Since the signal is normally varying less than 15 Hz/sec, the voltage measurement is sufficiently fast to allow errors due to signal variation during measurement to be neglected.

To make a measurement, a digital command from the DCU to the crossbar scanner chooses the proper channels to be measured. The selected analog signal is routed to the DMM where a command from the DCU directs the corresponding function, voltage in this case, to be measured and processed in digital output terms for transfer to the display unit and the DCU. Once the process has been completed, the DCU receives a signal from the DMM indicating that the analog signal has been processed and is ready for transfer.

A digital signal from the DMM is received by the DCU in both the monitoring and controlling phases. In the controlling phase, the DCU operates on the digital signal to determine an output signal needed to drive the process to the desired value.

The next subsystem to consider is the digital-to-analog converter, illustrated in Fig. 2.5, which takes the digital control output signal from the DCU and converts it to the analog signal used to drive the SCR power controller. The need for a 0 to -9 volt input signal to the SCR power controller resulted in the selection of a standard digital-to-analog (D/A) converter having an output level of 10 volts. The D/A chosen will convert a 12 digit binary number into an analog voltage proportional to the binary number. Thus, a 10 volt full-scale output is capable of being divided into 2^{12} or 2096 increments. This allows control of the analog signal to within 2.5 millivolt. Coupled to the output of the D/A is an operational amplifier with a negative unity gain factor which converts the positive output of the D/A to a negative signal compatible with the SCR power controller.

DIGITAL CONTROL UNIT

The heart of both the monitoring and controlling phases is the DCU. Designed around a PDP 11/20 digital processor, the DCU is coupled to peripheral components, Fig. 2.6, through appropriately designed interfacing. Each component can be polled individually by the processor and

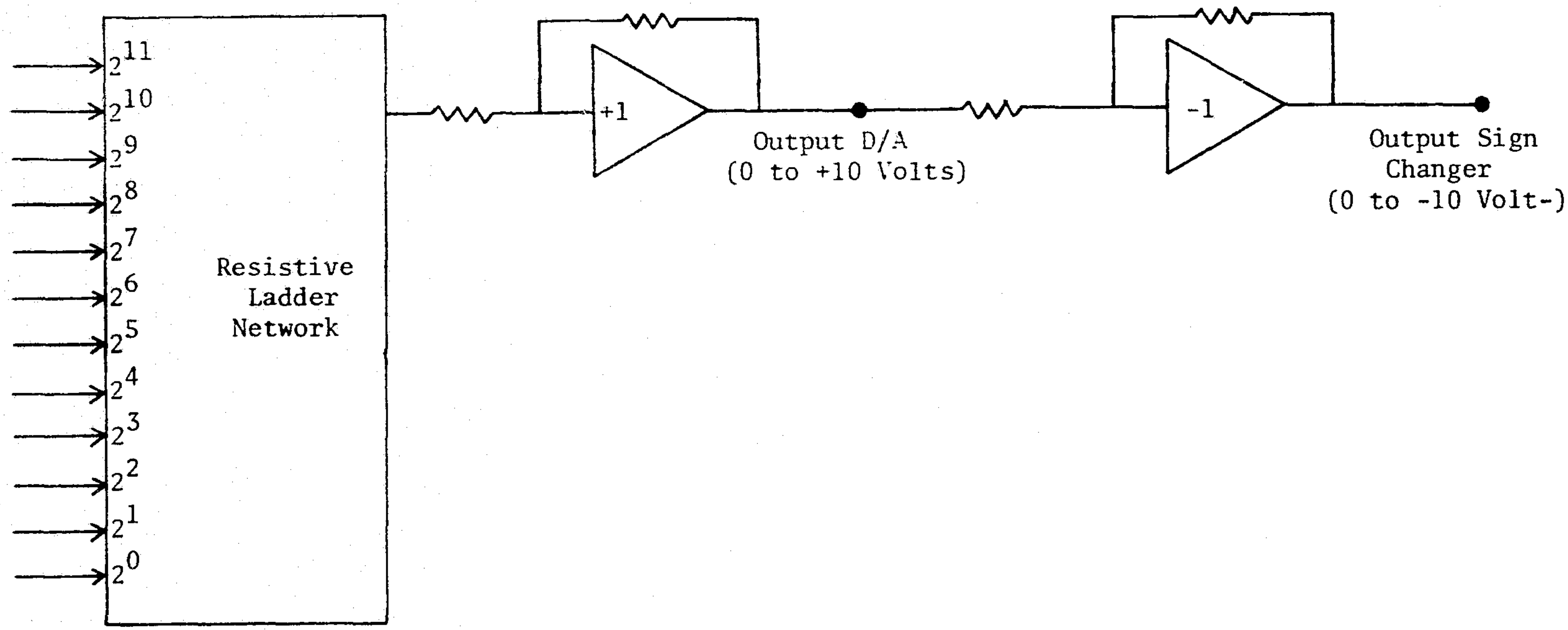


Figure 2.5. Digital-to-Analog Converter

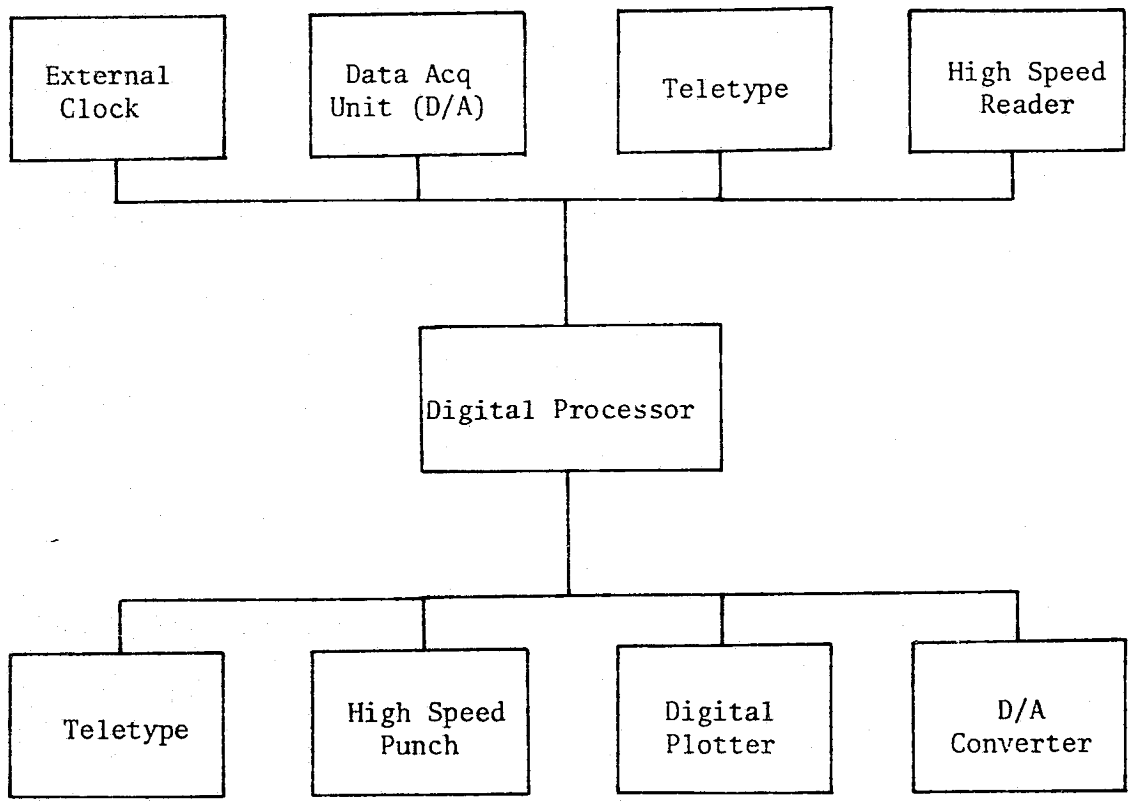


Figure 2.6. Digital Control Unit

data either transferred from the processor or from the peripheral device to the processor.

Probably the most important peripheral item is the teletype, because of its capability to converse with the processor in a conversational manner familiar to both the user and the processor. The next most important subsystem is the High Speed Reader/Punch (HSR/P). This unit makes it possible for pre-punched data tapes to be read by the processor. The processor can also use the HSR/P to punch data stored in its memory onto a paper tape for further analysis. In a similar manner the processor uses the digital plotter to plot the rate and control signal data taken during the monitoring and controlling phases.

The next peripheral device considered is the general purpose interface (the DR11-A) which allows various digital data to be interfaced to the processor. The DR11-A is the interface between the processor and the real world in both the monitoring and controlling phase of the processing. As illustrated in Fig. 2.7, connected to the DR11-A, via a 4 channel multiplexer, is various peripheral hardware including the D/A, A/D, DMM, crossbar scanner, and an external clock.

The external clock is used to indicate to the processor, at uniform discrete time segments, when it is time to perform certain functions. The primary purpose of the external pulse clock is to allow the processor to take frequency data at precisely one second intervals.

The "work horse" of the digital control unit is the PDP 11/20 digital processor. A high speed processor with an average cycle time of 1 microsecond, the processor is capable of acting as a "stand alone" unit for independent problem solving. It can also be used in conjunction

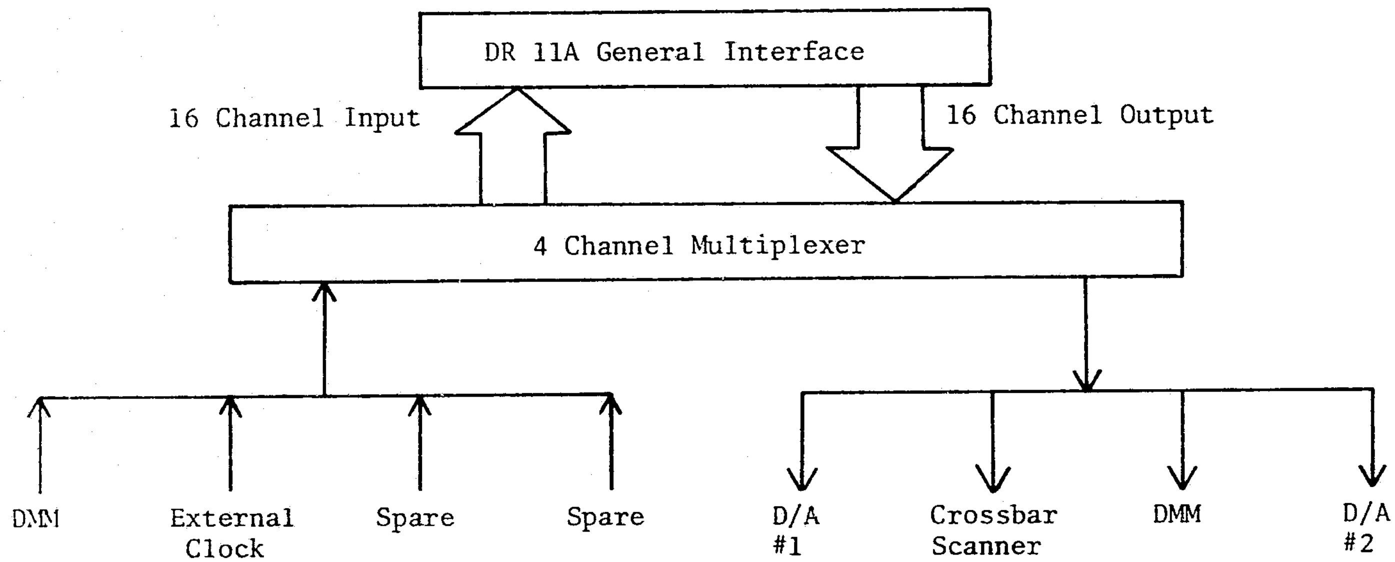


Figure 2.7. General Purpose Interface Diagram

with the data acquisition unit for various testing functions. A version of the Dartmouth BASIC programming language coupled with a machine language instruction set makes the processor an effective hybrid system for monitoring or controlling the thin film deposition process.

This chapter has described the hardware involved in both the monitoring and controlling phases of the deposition process along with the integral hardware required to carry out the actual deposition process. The following chapters will describe the techniques and algorithms capable of monitoring and digitally controlling the deposition process.

Chapter 3

MONITOR TECHNIQUE

As indicated in Chapter 1, the problem being considered entails three aspects, i.e., the development of the hardware to monitor and control the deposition process, the development of the procedure and software to monitor the deposition process under control of the analog unit, and the development of the procedure and software for an analysis of the digital control technique. The first aspect, the hardware to monitor and control the process, was discussed in Chapter 2. This chapter will explain the monitoring technique used to gather information from the analog system.

It should be noted that the monitoring technique described in this chapter is similar to the technique used to acquire data for the controlling process. The primary difference between the monitoring phase and the control phase is that the monitoring technique described in this chapter is written primarily in BASIC, while the monitoring software used in the digital control section is written in a Programmable Assembly Language (PAL).

Two parameters of interest during the deposition process are the rate of deposition and the input signal to the SCR power controller. The deposition rate is desired in order to have a reference for comparing the effectiveness of the digital controller versus the analog controller and because it is the primary function controlled. The input signal to the SCR power controller is an indicator of the response of the deposition rate output to a given input.

The function of the monitoring algorithm is to measure the frequency shift from the quartz-crystal monitor and the SCR power controller at fixed intervals of time, calculate a rate of deposition, and "massage" the data for output in various formats under user control. For accuracy, the DC output of the quartz-crystal monitor unit is used as the source of the low frequency shift data, while a direct connection to the inputs of the SCR power controller acts as the second source. Both signal sources are connected to separate input channels of the crossbar scanner for access by the DMM under control of the digital processor. Using the external digital clock to obtain an accurate and equally spaced measuring sequency of one set of data per second, the digital processor, through the use of the BASIC program (Appendix A), periodically collects the data from the two sources.

To accomplish the monitoring of a particular deposition run under control of the analog controller, a BASIC program, interfaced with an assembly language program, is utilized. Figure 3.1 illustrates the flow diagram for the monitoring procedure. Initialization of the variables, such as the number of seconds of monitoring, is input into the algorithm via the teletype. Once execution commences, the BASIC program retains count of the number of samples taken while an EXTERNAL FUNCTION routine, which is explained later in the chapter, monitors the digital clock input until a pulse is received. Upon receiving the signal, the algorithm transfers control from the clock monitoring routine to the routine that sets the crossbar scanner to the proper channels, polls the digital multimeter for the voltage value of the DC signal and the

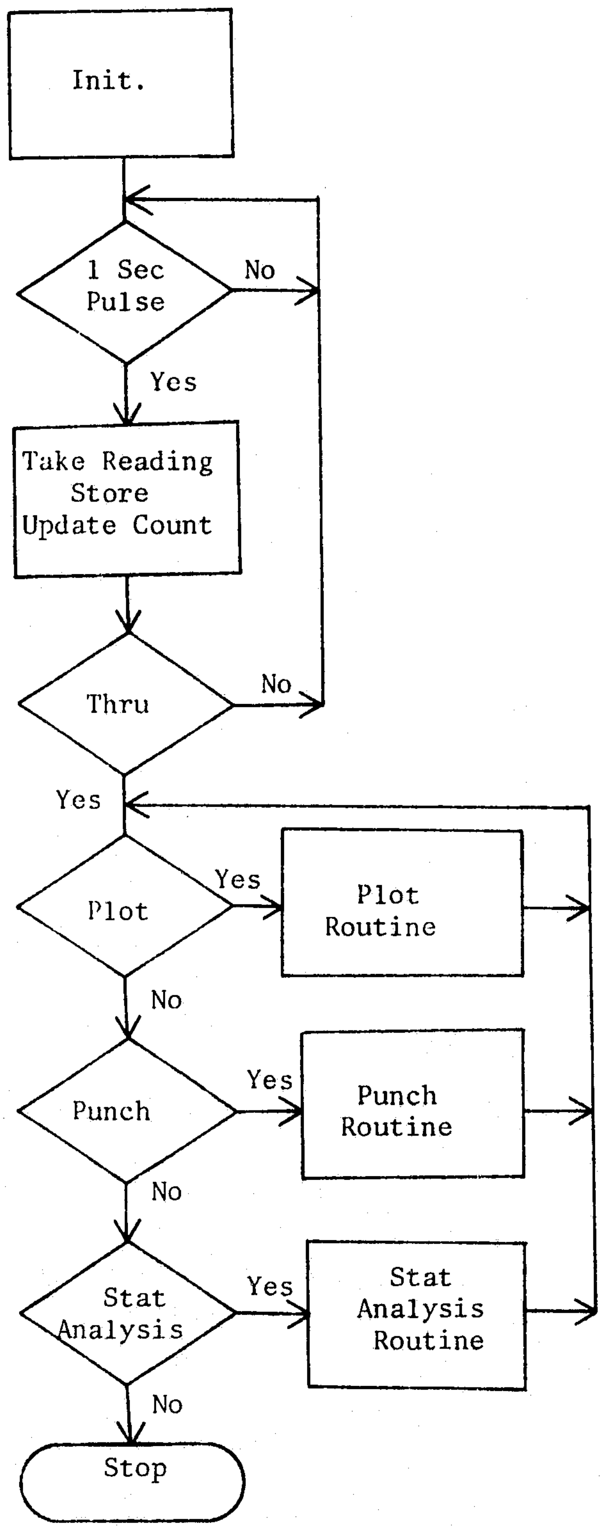


Figure 3.1. Monitoring Routine Flow Diagram

SCR power setting, stores the results internally in memory, updates the sample counter, compares this count with the desired count, and either transfers control to the clock monitoring routine or "drop" through to the output portion of the routine. At the drop through point of the algorithm, a decision to choose a rate or SCR plot, a punch tape, or the statistical analysis of the data has to be directed to the processor via the teletype input.

Prior to the execution of the plotting routine for the rate data, the DC voltage data corresponding to the measured frequency have to be digitally differentiated with respect to time to obtain the data in terms of rate units. Using the time interval between sampling as the base time for differentiation, the rate of change of the DC signal per second can be calculated using the relation

$$\frac{\Delta(DC)}{\Delta t} = V_i - V_{i-1} \qquad i = 2,3,4... \tag{3.1}$$

where V_i is the voltage reading obtained from the frequency to DC converter at the i-th second. In order to convert (3.1) to units that have meaning, i.e., Hertz or Angstroms/sec., the voltage values have to be multiplied by a constant of proportionality

$$\frac{\Delta(FREQ)}{\Delta t} = \text{Rate } i = M1 \cdot (V_i - V_{i-1}) \quad i = 2,3,4... \tag{3.2}$$

where M1 is the proportionality constant. The value of M1 in Hz/sec can readily be obtained from the slope of the calibration curve shown in Fig. 3.2(b). By multiplying this value of M1 by the corresponding evaporant slope of the Hertz-Angstrom curve, Fig. 3.2(a), the rate in

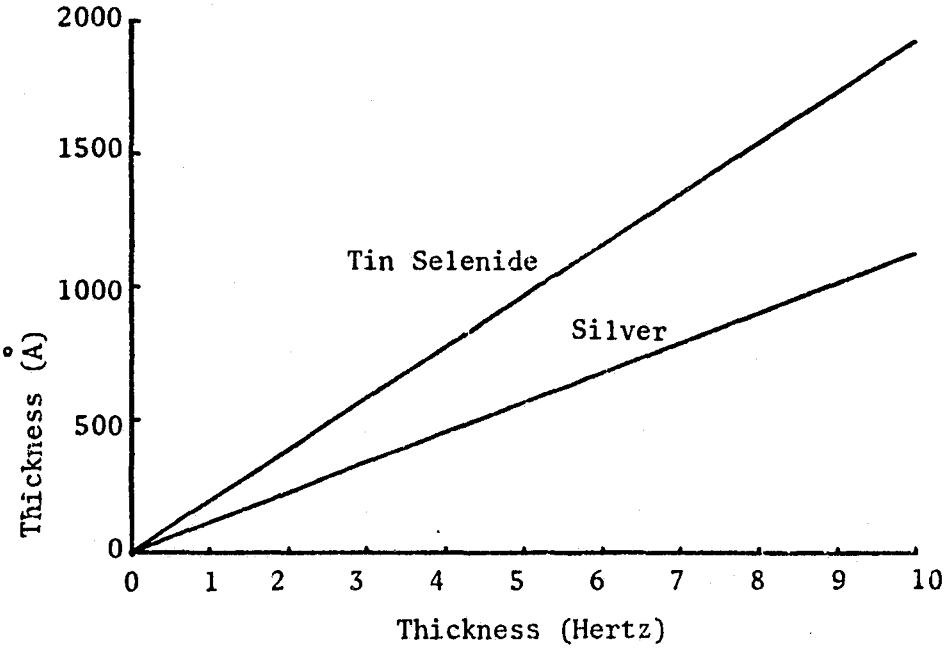


Figure 3.2(a). Thickness Conversion (Angstroms-Hertz)

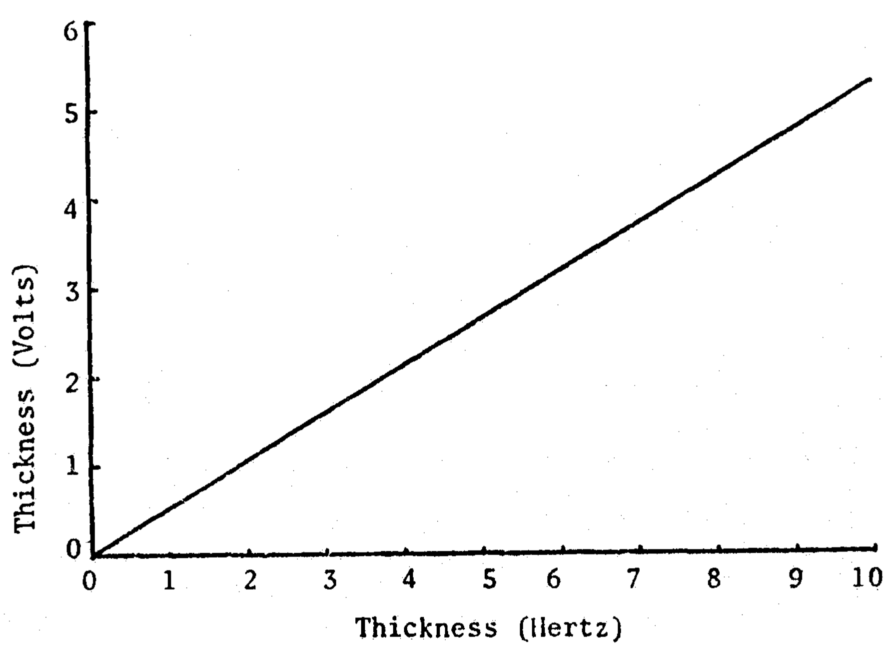


Figure 3.2(b). Thickness Conversion (Volts-Hertz)

Angstroms/sec can be obtained. Since the slope of the DC conversion to Hertz is independent of material, while the Hertz-Angstrom curve is dependent upon the density of the evaporant material, the primary analysis conducted in later chapters is with reference to the Hertz relationship in order to give a common base for the analysis.

The conversion of the frequency data to rate data is needed for two purposes. The first is to plot the rate, along with the SCR power controller input, throughout the deposition process for use in analysis of the data. The second purpose is to be able to perform statistical analysis upon the rate data and establish a mathematical basis for comparison of the two controller techniques.

To perform the statistical analysis, routines to calculate the mean value of the rate and the standard deviation about the mean are incorporated as part of the analysis routine. The rate data calculated from (3.2) are used to obtain the standard deviation through the relationship

$$\mu_R = \frac{1}{K_2-K_1+1}\left[\sum_{i=K_1}^{K_2} R_i^2 - \frac{\sum_{i=K_1}^{K_2} (R_i)^2}{K_2-K_1}\right]^{1/2} \tag{3.3}$$

where μ_R = Standard deviation of the mean rate

R_i = Rate at the i-th second

K_2 = Last rate data point

K_1 = First rate data point

The mean value of the rate, R_{12}, over the time interval $K_1 + 1$ to

K_2, can be calculated using the rate value of (3.2) substituted in the statistical mean equation, i.e.,

$$R_{12} = \frac{1}{K_2-K_1+1} \sum_{i=K_1+1}^{K_2} R_i \tag{3.4}$$

Simplification of (3.4) can be made by substituting (3.2) to obtain,

$$R_{12} = \frac{1}{K_2-K_1+1} \sum_{i=K_1+1}^{K_2} (M1*(V_i-V_{i-1})) \tag{3.5}$$

or expanding (3.5) we obtain

$$R_{12} = \frac{1}{K_2-K_1+1} (V_{K_1+1}-V_{K_1}) + (V_{K_1+2}-V_{K_1+1}) + \ldots$$

$$+ (V_{K_2-1}-V_{K_2-2}) + (V_{K_2}-V_{K_2-1}) \tag{3.6}$$

Examining (3.6), it can easily be seen that the positive term in every group is cancelled by the negative term in the succeeding group except for the last group. Carrying out the subtraction, (3.6) will reduce to

$$R_{12} = \frac{M1}{K_2-K_1+1} \left[V_{K_2} - V_{K_1} \right] \tag{3.7}$$

Thus, to calculate the mean value of the rate signal over a given time interval only the voltage measurements at each end of the interval are needed.

After the plotting of the rate data and SCR data along with the statistical analysis of the rate data, see for example the run illustrated in Fig. 3.3, the internally stored raw data are punched on paper tape using the high speed punch. This results in a permanent copy of the data that can easily be "read" by the digital processor.

The routines described, including the algorithms for the statistical analysis, are performed by the previously defined hardware under software control. As explained, a hybrid choice of software, i.e., BASIC and PAL, was chosen. The choice of using BASIC as the primary language for the monitoring phase was based on the ease of constructing and editing a BASIC program. Since the only function being completed during each second of monitoring consisted of storing in memory the two DMM readings, slow execution speed of BASIC did not have an effect on the choice of languages. However, speed of execution had to be considered in the choice of the PAL programs interfaced with the BASIC routine.

The EXTERNAL FUNCTION call, the method by which BASIC programs are interfaced with a machine language portion, allows the user to write subroutines in the machine's language instruction set in order to increase the speed of an operation. As an example, to calculate the statistical analysis for a 550 second deposition period, a routine written in machine language requires less than 20 seconds.

Since the routine was rigidly fixed for the statistical analysis portion of the routine, the added effort required to program in PAL was worthwhile. However, writing the entire program in PAL while maintaining the flexibility which allowed ease of editing was not possible. Thus, a hybrid set of software maintaining the speed in redundant operations and the flexibility for user augmentation was used.

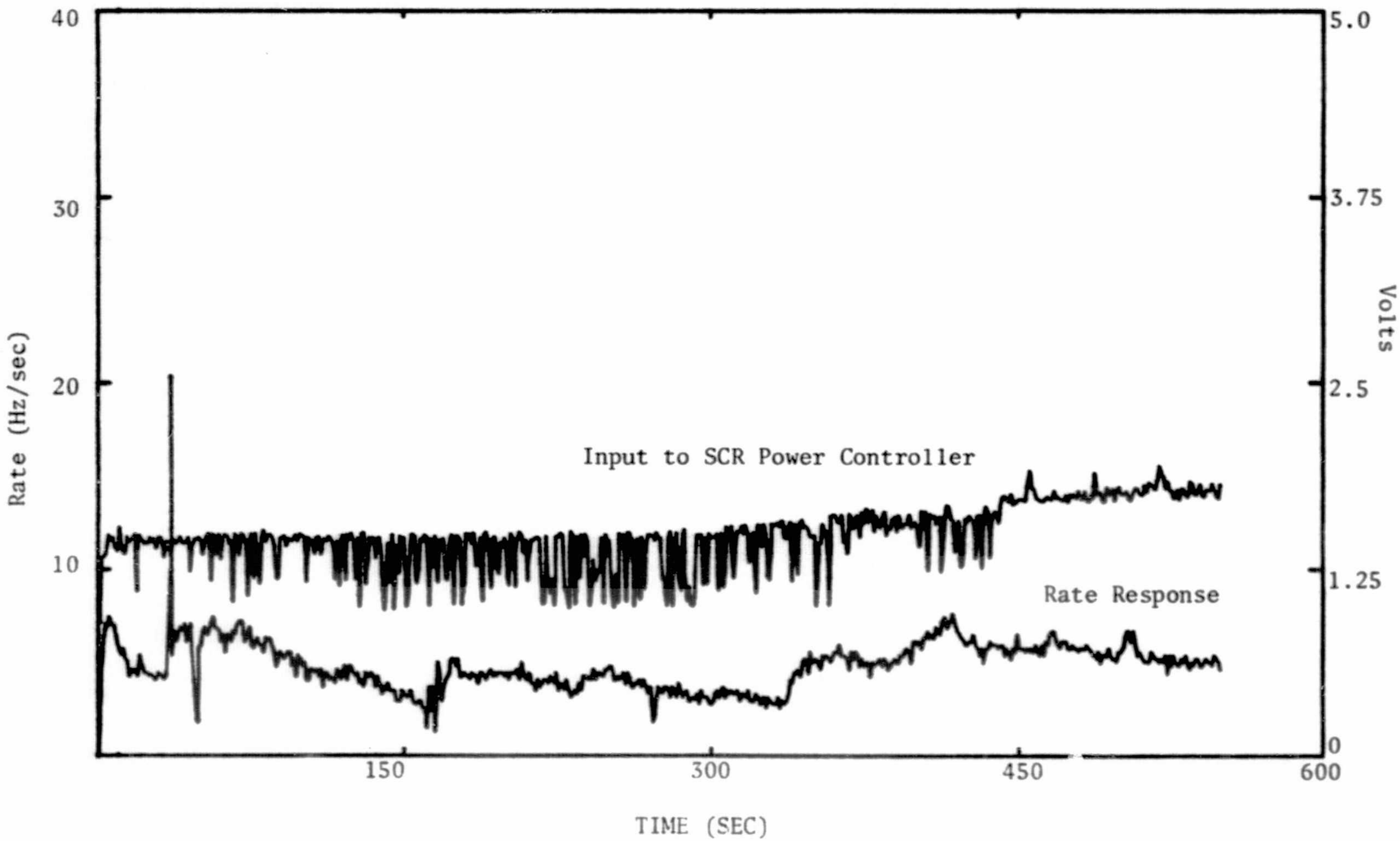


Figure 3.3. Deposition Measurement Mode with Monitoring Hardware

This chapter has illustrated the monitoring technique used to obtain data for both analysis of the system and as a base of comparison. The algorithm required to monitor a deposition and plot and analyze the data has been given. The next important factors to consider are the algorithms and routines needed to implement the digital controller and close the feedback loop of the deposition process.

Chapter 4

CONTROLLER DEVELOPMENT

Once the hardware and software requirements necessary to allow monitoring and controlling of the deposition, as described in previous chapters, have been dictated, the software algorithm to close the control loop through the digital processor needs to be developed and implemented. This chapter will establish the control algorithms that were investigated along with associated problems encountered and their solutions. Initial studies indicated that because of the complexity of the system, as indicated in Chapter 2, an adaptive controller was desirable. With this approach selected, a scheme similar to the work of Kalman [13] was investigated. To control a second order system Kalman developed an algorithm that resulted in minimum time to steady state with minimum overshoot. He illustrated his technique using a second order system as illustrated in Fig. 4.1.

Mathematical approximation of the deposition system implied a second order system was the appropriate model. This hypothesis resulted from an analysis of each subsystem by estimating its response to a step input. For the second order closed loop control system illustrated in Fig. 4.1, the control law established by the Kalman technique had the form:

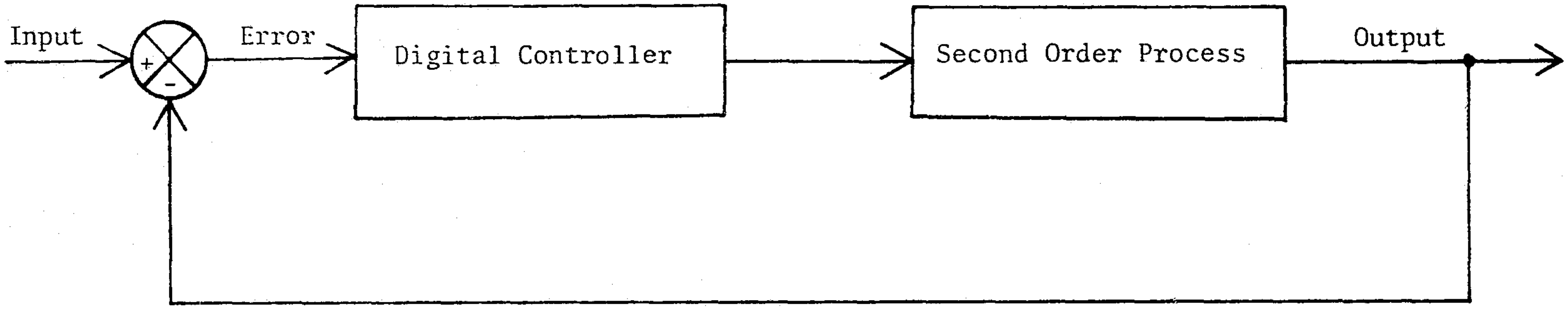


Figure 4.1. Block Diagram of Second Order Control Process

$$[a_1(N) + a_2(N)]M_k - a_1(N)M_{k-1} - a_2(N)M_{k-2}$$

$$= e_k + b_1(N)e_{k-1} + b_2(N)e_{k-2} \tag{4.1}$$

Where

a_1, a_2, b_1, b_2 = the adaptive coefficients to be updated periodically,

M_k = the controller output at the k-th sample,

$e_k = r_k - c_k (k=1,2,3\ldots)$ = the system error at the k-th sample,

r_k = desired rate value at the k-th sample, and

c_k = measured rate value at the k-th sample.

By manipulation of (4.1), the controller output for a given sample can be calculated by

$$M_k = [a_1(N)M_{k-1} + b_1(N)M_{k-2} + e_k + b_1(N)e_{k-1}$$

$$+ b_2(N)e_{k-2}]/[a_1(N) + a_2(N)]. \tag{4.2}$$

Therefore, the controller output as described in (4.2) is a function of the history of the past controller outputs, M_{k-1} and M_{k-2}, along with the influence of the present errors, e_k, and the past errors. Kalman proved that for a second order system the adaptive coefficients should be updated every third sample period. That is, the controller uses a set of adaptive coefficients to control the process for three time periods and between the third and fourth period a new set of coefficients is calculated.

His work indicated that the algorithm was independent of the initial values chosen for the coefficients, but that after a short processing time, the coefficients would converge to a set of values that would drive the system to the desired response. If the initial coefficient values were not close to the steady state values, an unstable response could occur. Assurance that the controller was inherently stable and that the coefficient would converge was given by Kalman.

After incorporating the Kalman adaptive coefficient controller in the software of the digital processor, many attempts were made to achieve the indicated success that Kalman experienced. Theoretically, the technique should have worked but in reality results less than optimal were obtained. Allowing the adaptive controller to operate with no restrictions on any of the coefficients or control outputs, the algorithm should have driven the coefficients to the necessary values to achieve the desired control characteristics. Initial processing with the controller in an unrestrictive mode resulted in unsuccessful control in that the coefficients were not converging toward a set of values nor was stability being achieved.

Analysis of the controller response to calculated error signals indicated that the controller was attempting to obtain control by driving the system in the proper direction to achieve the desired response. After a period of time, the system response due to high output values from the controller were beyond the measuring constraints of the hardware. At times, due to low indications, the controller would calculate SCR power settings that would turn the electron gun on full power, a condition that would soon burn out the gun and crucible assembly. At the high output setting, the system would attempt to achieve a rate so high that material would literally boil out of the crucible. A software constraint to limit the maximum controller output appeared to prevent overloading of the electron gun.

Initial constraints limiting the minimum and maximum values the controller could transmit to the D/A unit had shortcomings in that this did not appear to give the adaptive process the freedom to operate in an unrestrictive mode. Some convergence was experienced by the new technique, especially for initial coefficients near a stable condition, but the response was inadequate as a replacement for the analog rate controller.

As a corrective measure, instead of calculating a new D/A setting at the end of each controller sample, as indicated by (4.2), a "delta" change to the previous controller setting was calculated. This technique, coupled with the maximum/minimum controller restriction, would allow only a small change to be added or subtracted from the past D/A setting.

To incorporate this change, the D/A input value at the end of the soak routine was stored within the memory. At the completion of a controller calculation the output was compared with the maximum/minimum restriction and the resultant correction added/subtracted to the D/A setting. That value was then passed to the D/A input and into the memory for use at the end of the next controller calculation. Mathematical changes were made to (4.2) to obtain the new control algorithm:

$$\Delta M_k = [a_1(N)M_{k-1} + b_1(N)M_{k-2} + e_k + b_1(N)e_{k-1} + b_2(N)e_{k-2}]/[a_1(N) + a_2(N)] \tag{4.3}$$

Several deposition attempts using (4.3) as the control law brought results similar to those experienced previously. Analysis of the rate response and the controller output indicated that initial coefficient values could be chosen to generate stable responses. During the successive control calculations following an update the output would take a significant jump on the first sample and then slowly take insignificant adjustments in an attempt to drive the response toward the desired value.

This problem appeared to be due primarily to the system's not having enough time to respond to the controller output. Since the adaptive coefficient process relied upon the response of the system to the output, a one second sample time for a system taking several seconds to respond to a given input was insufficient. With a software modification, the controller was adapted to take rate data at one second intervals while the controller output time interval was periodically updated as dictated by the user.

Software restrictions required that the sample time be taken in multiples of three seconds, i.e., on the first, fourth, seventh, etc., seconds of processing. This restriction was because of the necessity of placing the proper k-th error and post error in the correct sequence of the software.

Attempts at varying the sample time also met with limited success. Restrictions on the amount of variations in the coefficients, selection of coefficients, update or sample time variation, and restriction of the amount of change between control settings had little effect on the convergence/divergence of the coefficients. A detailed analysis of the software indicated that a problem existed in the implementation of the software in the digital processor. Hardware restrictions on the processors' word structure placed a limitation on accuracy which could be expected from the calculations involving very large and very small values. When this limitation was applied to the matrix inversion routines used to update the coefficients, it was noted that the accuracy needed to perform the inversion was not within the scope of the software or hardware of the DCU.

Because of the numerical limitations that restricted the use of the adaptive process originally proposed, a fixed coefficient controller was implemented. Using the basic control law established in (4.3) along with successive iteration of the coefficients, attempts were made to tune the fixed coefficients. Based on the response of the controller with the human factor in the feedback loop to update the coefficients, a set of coefficients was derived that appeared to give reasonable control of the deposition process. Although the control was inferior to the analog rate controller, it appeared to be the best that could be achieved from the given algorithm.

An analysis of the response of the controller is illustrated in Fig. 4.2. The characteristics of the algorithm indicate a predominant lag between the response and the input. This resulted in the controller's always overreacting to the response of the deposition process. When the rate exceeds the desired rate, as shown in Fig. 4.2, the controller does not cut back on the input power until the response has passed through the desired rate. For a fast responding system this controller would normally be damped. However, for a slow responding system such as the deposition system an adequate damping factor could not be achieved.

Various parameter variations were implemented in an attempt to increase the damping factor while maintaining a marginally stable system response. After attempts to tune the coefficients were unsuccessful it was decided that possibly the type system had been erroneously chosen

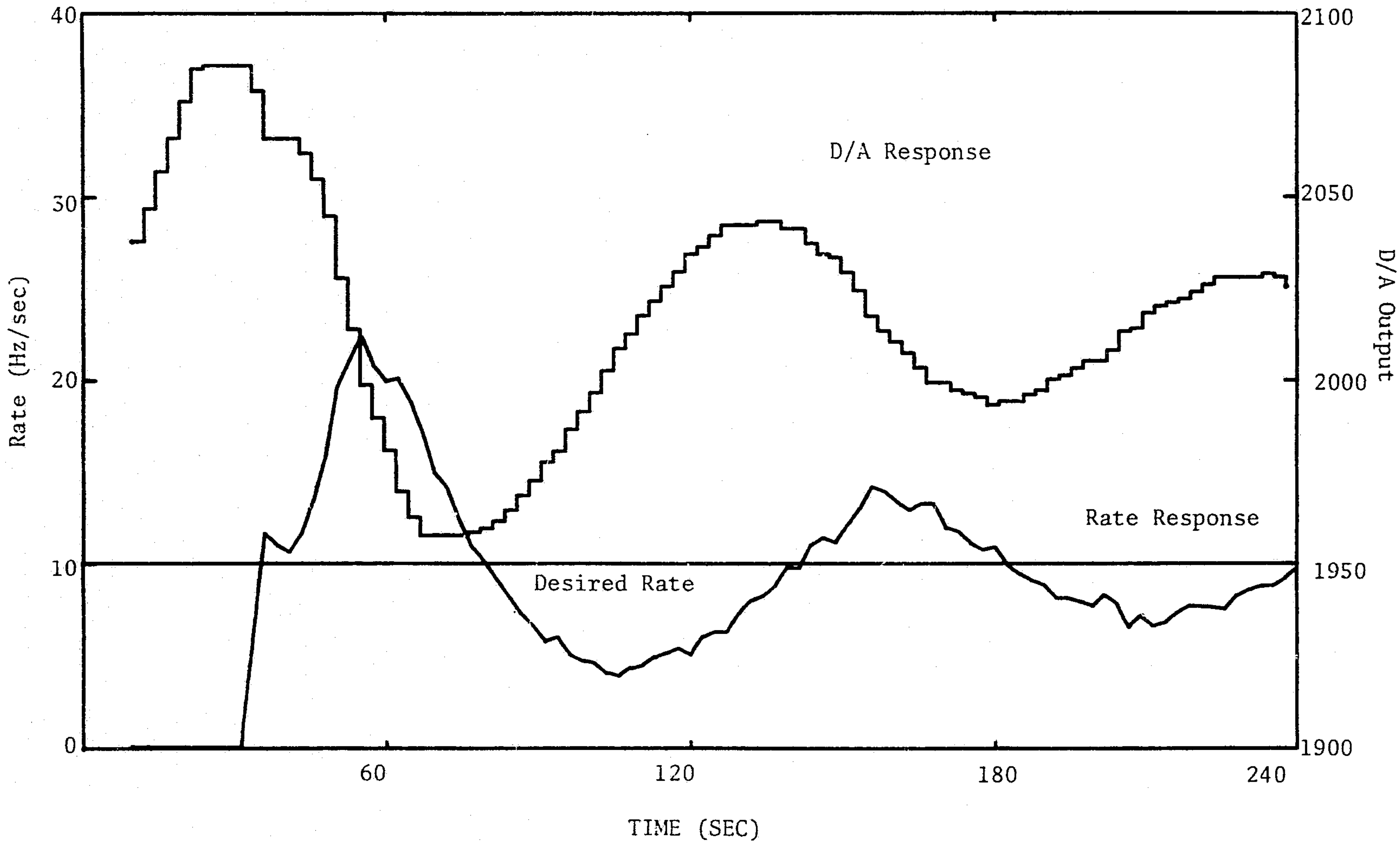


Figure 4.2. Phase Lag Controller Response

or that the chosen coefficients were far from the correct coefficients required for stability.

Further analysis indicated that control might be obtained if the controller could sense the rate of change of the response and adjust accordingly. With this hypothesis formulated, a new algorithm was developed. Assuming a controller output proportional to the error and rate of change in the error, the following algorithm was obtained.

$$\Delta M_k = e_k + W*\dot{e}_k \tag{4.5}$$

where W is a coefficient that determines the effect of the rate term on the output. Known as a Lead Phase Compensator, (4.5) describes an algorithm which has the properties of improving the time response of the system by the introduction of anticipation into the controller.

Implementation of (4.5) into the software can easily be achieved by setting the values of (4.4) to:

$$\Delta M_{k-1} = \Delta M_{k-2} = 0 \tag{4.6a}$$

$$a_1 = a_2 = 1 \tag{4.6b}$$

$$b_2 = -b_1 = W \tag{4.6c}$$

$$e_{k-2} = e_k \tag{4.6d}$$

Thus, (4.4) becomes

$$\Delta M_k = e_k + W*(e_k - e_{k-1}) \tag{4.7}$$

which is the digital representation of (4.5) for implementation in the processor.

The first attempts to employ (4.7) brought successful results well beyond those achieved with any other technique that had been previously investigated in this work. The controller was able to control the response of the deposition process to the desired degree while maintaining it within a small variation about the mean.

Variation of the velocity multiplier, W, indicated that the stability of the control process had a dependence on the velocity parameter. Test runs with both a metal (silver), and a semiconductor (tin selenide), were conducted to determine the dependency of the stability on the velocity term. The standard deviation measurement about the mean was used as the measurement indicator. Initial test runs indicated dependency of the controller on both the sample time and the velocity multiplier. Thus, the tests were modified to incorporate the sample time variation as one of the dependent variables.

This chapter has illustrated the evolutionary process which the digital controller algorithm underwent to reach the form of (4.7). The following chapters will explain the software used by the digital controller and the results of the parameter tuning effort along with the results of the final control algorithm.

Chapter 5

DIGITAL CONTROLLER SOFTWARE DESCRIPTION

This chapter will describe the software methodology utilized to incorporate the control algorithm established in Chapter 4. The software written to control the deposition process differs from the monitoring software primarily by the type language used to implement each. In the case of the monitoring software, a hybrid combination of the conversational language, BASIC, and the machine language, PAL, was incorporated for ease of programming.

To implement the control process, only the machine language, PAL, is used in order to facilitate the speed asset that can be obtained. Besides taking the frequency measurement in the one second interval, the control algorithm calculates a rate based on the frequency measurement, calculates a D/A setting based on the rate error, adjusts the multiplexer to receive and transmit the proper data, sets the D/A input to the calculated value, and, finally, punches all the data on the high speed punch. Thus, it becomes apparent that speed of execution is the primary driving function for the choice of the machine language.

To illustrate the speed that can be expected from the processor, the nominal instructions including single word adds, subtracts, compares, and branches require approximately 1.5 microseconds for execution. Coupled with a floating point math package capable of performing floating point operations in milliseconds, the language structure lends itself to sophisticated programming.

Not only are algorithms to take voltage measurements, to calculate rate values, and to calculate control outputs needed to complete this task, but support algorithms to perform the rise, soak, data punching, and other "housekeeping" functions are required for a unified software package. Figure 5.1 depicts the organizational structure of the finished software package. A description of each of the modules in the figures, along with the interaction of each, will be covered in this chapter. A listing of all the routines is contained in Appendix B.

SOFTWARE MODULE DESCRIPTION

To have a dynamically interactive software structure, that is, one that interacts with the user during execution, a structure based on a priority interrupt system was developed. Assigning priority of execution to different devices such as the teletype, digital clock, high speed punch, D/A, and power fail hardware, required software that relies on an interrupt signal from a given device. This was developed to effectively and efficiently incorporate the associated service routines. To illustrate, the power fail has top priority which means that whenever this device interrupts the process, any routine being executed will stop and allow the power fail routine to be executed. If a device of priority level equal to the device being serviced attempts an interrupt, the interrupting device will have to wait.

The interrupt controller, illustrated in Fig. 5.2, will be the first module considered. The interrupt controller is composed of the teletype, the pulse clock, the initialization routine, and the trap handler. The first routine entered on loading the program is the module titled MAIN, which initializes the hardware by setting the proper channel

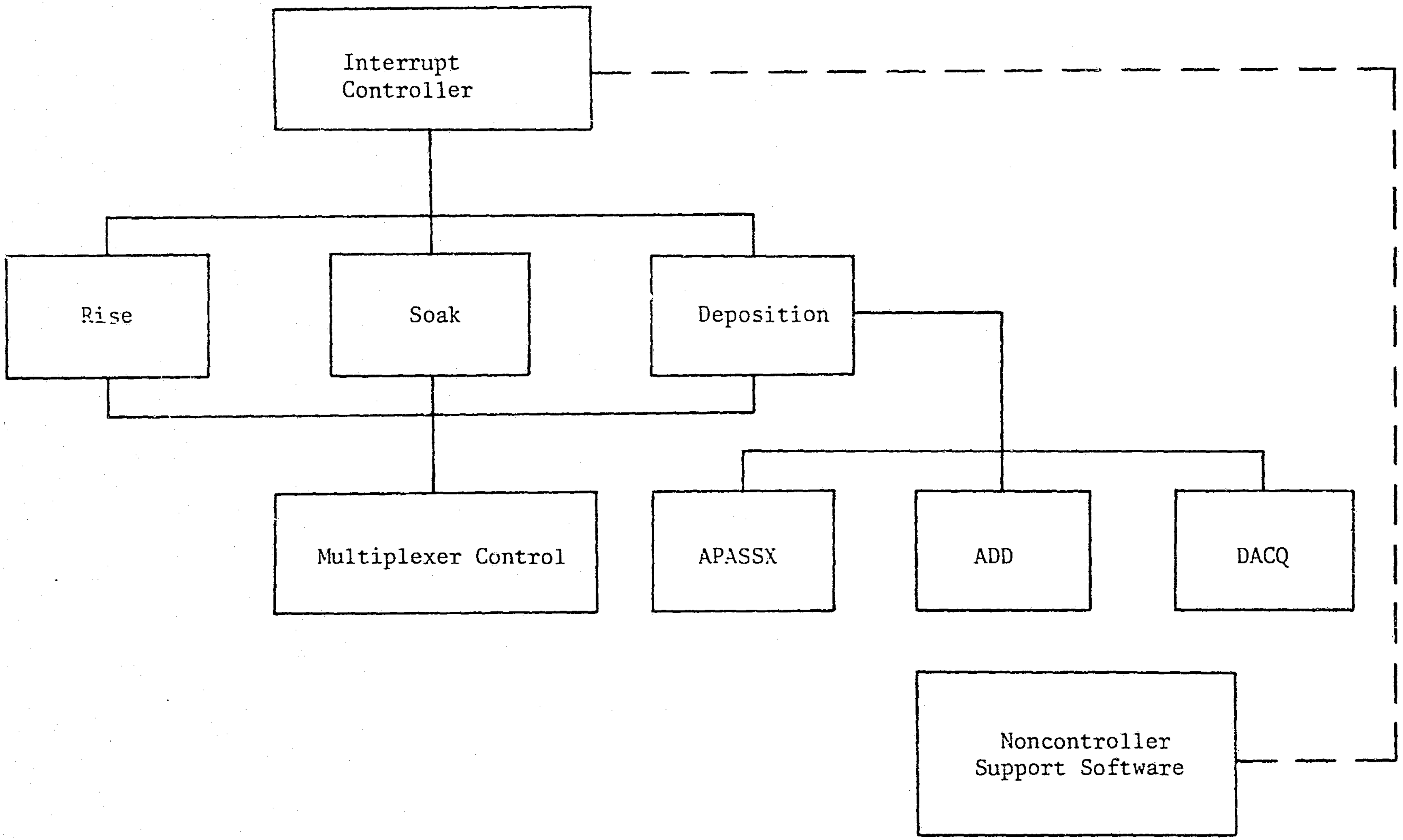


Figure 5.1. Digital Controller Software Structure

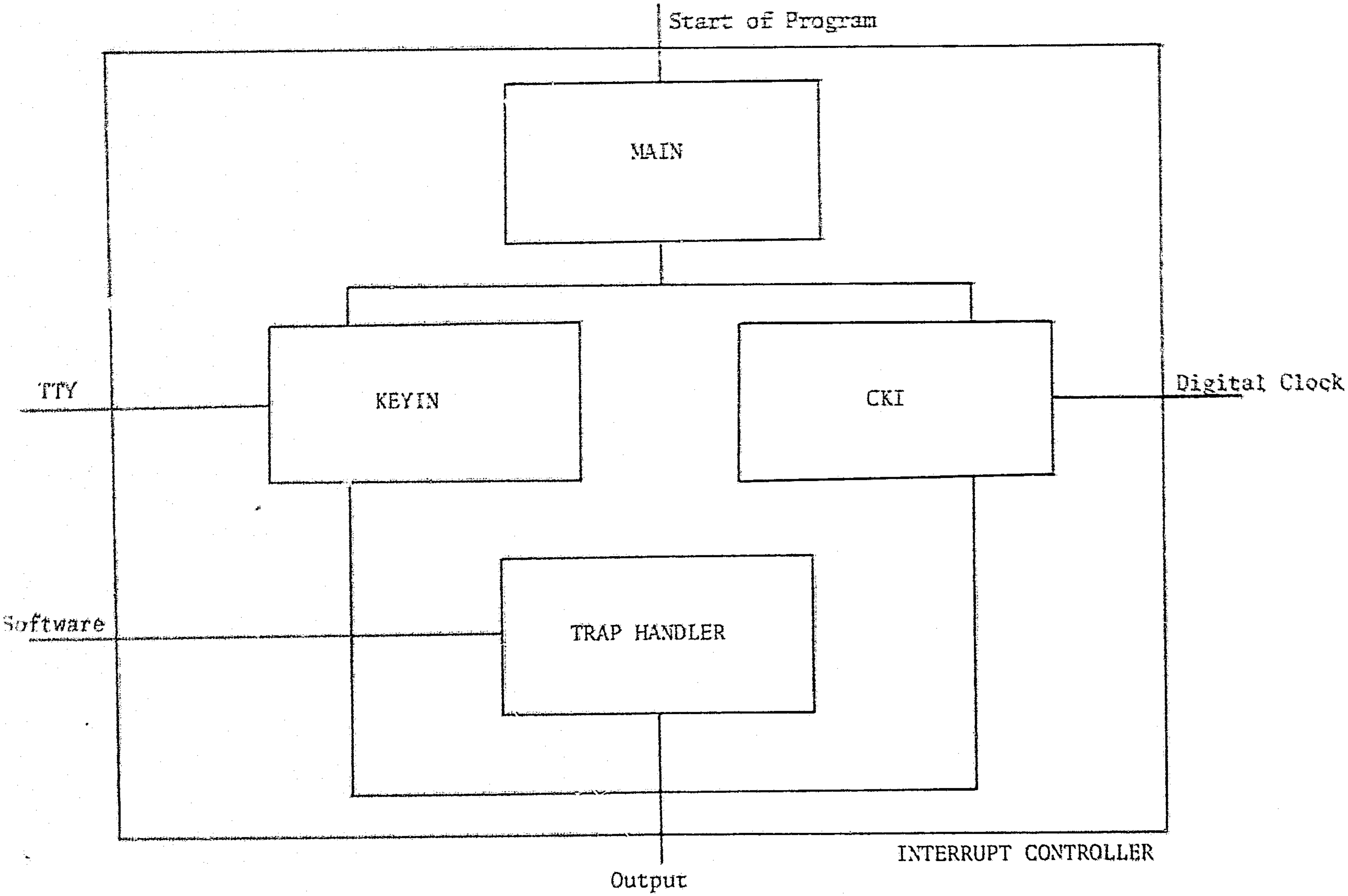


Figure 5.2. Interrupt Controller Block Diagram

on the D/A unit, encodes the DMM to take a voltage reading, and finally transfers control to the next module, KEYIN. The MAIN routine, entered each time the clock pulse causes an interrupt, determines the deposition status.

After hardware initialization is completed, the teletype interrupt enable line is made available. Any time a character is struck on the teletype, a hardware interrupt is sensed by the processor. If there is no other routine being executed with a higher priority, the KEYIN routine is entered and the character which is struck is evaluated. If the character isn't recognized as a (CTRL P), (control "P"), KEYIN ignores the input. Entering CTRL P and having it evaluated results in a response from the processor to the user. The colon symbol, ":", is output to the teletype and control is transferred to the INPUT/OUTPUT EXECUTIVE, (IOX) which operating in an interrupt mode receives, echoes, and stores in memory any inputs from the teletype. Once the return key, symbolizing an end to the input, is entered IOX returns the message to KEYIN for evaluation. Thus, KEYIN, coupled with the IOX routine and operating in an interrupt mode, relieves the processor from continually monitoring the teletype for an input and allows entry to software when no other routines are being executed.

It is through the KEYIN routine that the variable data for the coefficients of the controller, the time variables such as rise, soak, and deposition time, the punch requirements, the execution commands, and the desired rate of deposition are input to the processor via the teletype. Not only can the variables be input via KEYIN, but the values of the input parameters can be verified through the same routine.

Since it is an interrupt-controlled software structure, the processor can be polled at any time by the user via the teletype with a subsequent change entered for one of the variables. As an example, during the deposition routine, if it is desired to change the rate of deposition, redefining the rate variable results in that variable's being immediately changed. The next calculation of an error signal for (4.7) will use the newly updated value.

KEYIN is the base module that accepts the commands of parameter definition, parameter status, or process definition. Without the interactive capability or the parameter assignment that KEYIN offers to the software package, any paramount variation would have to be binarily entered via machine language modification versus the convenient conversational mode.

As KEYIN functions to interpret commands from the teletype interrupts, the clock interrupt routine (CKI) functions similarly to interpret interrupts from the clock and select the proper service routine, i.e., rise, soak, deposition, or standby. During the execution of the program, one second pulses are sent from the external clock to the CKI routine. If the deposition process had been started, each clock interrupt would cause one of the above routines to be entered based on the condition of the flag settings within CKI. CKI directs the flow of the processor every time a clock pulse is sensed by the hardware.

The last routine within the Interrupt Controller is the trap handler routine which evaluates all the internally generated software traps. It performs standard software functions such as floating point manipulations, error message generation, and teletype input/output executive manipulation. Upon completion of the execution of a generated trap routine, as in all the interrupt controller modules, the interrupted process is resumed.

Control from the interrupt controller is passed to the rise, soak, deposition, or support software module for execution of a given function. Each of these modules will now be discussed with explanation of the function performed by each.

Rise

The RISE routine is incorporated to set the electron gun to a given power setting below deposition power and raise the power slowly to a soak setting sufficient to outgas the evaporant. From parameter values input to the routine via KEYIN, an initial and final power setting is calculated and stored in the process's memory. Upon entering the rise routine, an incremental increase for each time interval is calculated using the relation

$$\Delta\ D/A = \text{Integer}\ \frac{R_F - R_I}{T_R} \tag{5.1}$$

where R_F = Final Rise Value

R_I = Initial Rise Value

T_R = Rise Time (seconds).

The initial value, R_I, is transferred to the D/A thus establishing an initial power setting for the electron gun. At each one second interval, the D/A value is updated to a new value dictated by the prior setting plus the integer incremental value formulated by (5.1).

Evaluation of (5.1) will show that unless caution is taken so that the division process results in an integer value the final rise setting will be less than the desired value. As an example consider R_F,

R_I, and T_R to be 440, 240, and 60, respectively. Carrying out the calculation yields an incremental value of 3.333 units per update. Taking the integer value yields an operating incremental value of 3, which results in a final value of 420 instead of the desired 440. This minor limitation is not significant when compared to the time restriction the analog controller places on its rise routine. Using the analog controller a maximum rise time of 180 seconds can be achieved. However, using the digitally controlled rise routine a maximum rise time of 2^{16} seconds or 655,535 seconds can be achieved. For materials requiring long rise times such as quartz or platinum, the digital processor offers a definite advantage.

Soak

When the count, kept by an internal counter updated each clock pulse, reaches the set value for rise time, T_R, the rise flag is cleared and the process is transferred to the Soak routine along with the final rise value of the D/A. Similar to the Rise routine in the operation, the Soak routine maintains the final rise setting for a prescribed time, T_S, allowing the evaporant to complete the outgassing process. The Soak routine also offers the advantage that T_S can have any value up to 65,535 seconds.

Deposition

After the Soak routine has been executed for the preset time, control along with the D/A setting is passed to the deposition routine (DEPOS). Within DEPOS the digital control of rate parameter is executed. The control law equation developed in Chapter 4 is implemented by DEPOS with the aid of support software. Routines controlled by DEPOS perform

C-2

hardware manipulation, frequency calculations, and other "housekeeping" functions. It is within DEPOS that the control value output is compared with the maximum or minimum allowed value and the result transferred to the D/A.

Other functions completed by DEPOS include the calculation of the rate, the error, and the rate of change of error. At the end of each of the three time intervals of data processing, DEPOS structures all the parameter values, rate, D/A settings, and variable coefficients for punch by the HSR/P. In the interrupt mode, the processor passes a word of information to the HSR/P and then continues to process other routines until the punch interrupts the processor and requests more data. This "hand shaking" routine continues until all the data is punched on the tape.

In order to maintain modules of reasonable length, the DEPOS module has several support modules directly coupled as illustrated in Fig. 5.1. The largest of the support modules is APASSX which is tasked to calculate the error and the digital controller increment. In a support role via DEPOS to APASSX is the ADD module which algebraically adds the calculated controller increment to the previous controller output which is sent to DEPOS for comparison and finally transferred to the D/A unit.

DEPOS relies on the support module DACQ to perform the function of controlling the A/D unit. After supplying software codes which are compatible with the required hardware inputs, DACQ monitors the DMM until a measurement is completed. It then "reads" the data from the digital output and converts it to a format for utilization by DEPOS. Therefore, the interaction of DEPOS with its support modules, APASSX, ADD, and DACQ, completes the software manipulation needed to calculate control values.

Interface Controllers

Illustrated in Fig. 5.1 are the interface control modules which are common to all the processing routines. The CTLMDX, which can be entered from either the rise, soak or deposition routine indicating which devices require access from the processing routines. It then sets the proper channels on the four channel multiplexer allowing access through one DR11-A general interface input/output device to branch to four real world hardware devices.

Noncontrolling Support Routines

Also shown in Fig. 5.1 by the dotted lines are modules referred to as Noncontrolling Support Software. These modules, Power/Fail and DEBUG, are routines which support the total effort out are not directly utilized by the digital processor to complete the deposition control. The Power/Fail routine supports the processor in case the line voltage is interrupted during processing. Once the line voltage drops an interrupt with top priority is generated that gives the power/fail routine 2 milliseconds to perform its functions. In the 2 milliseconds all the working registers are stored in nonvolital memory. On power recovery, the routine resets the channel on the crossbar scanner and institutes a DMM reading to make sure all the hardware is set as it was prior to the power/fail. After the hardware is reset, all the working registers are restored and execution of the deposition program continues. This routine has proven itself valuable especially during thunderstorms where line flickers occur regularly.

The other routine which has been very valuable in debugging any software modification or changing any coded variable is the DEBUG module. On initial loading of the entire software into the machine, transfer is automatically made to the DEBUG module. The sample time, as discussed in Chapter 4, along with the starting address of the digital controller routine are input through DEBUG and transfer is made to MAIN.

When access is required of DEBUG, the KEYIN routine, coupled with the statement "DEBUG" typed through the teletype, causes transfer of execution to the debug package. DEBUG gives the user the capability of polling the contents of any memory location and having its contents printed on the teletype. If it is desired to change the polled contents, entering the desired contents on the keyboard will result in the value being inserted in the proper location.

Termination Modes

There are two possible ways to terminate the control process. One which is used extensively in the coefficient determination effort is a fixed-time mode for deposition. The fixed-time mode is implemented by placing a finite deposit time into the system. At the completion of the time span, the deposition is terminated and a message is printed out on the teletype. This mode results in equal deposition periods required for analysis purposes.

The alternate mode of termination, which is most advantageous for thin film device manufacture, is the fixed thickness mode. Once the deposition has started in this mode, the operator inputs a value for the end frequency which corresponds to a finite thickness. As an example, if a frequency shift of 10 KHz represents a desired thickness of 5000 Å and the presently displayed frequency value is 1500 Hz, a thickness value of 11,500 is entered via KEYIN along with a very high deposition time. When the frequency measurement reaches 11,500 Hz, the deposition process will cease.

Summary

All the routines discussed comprise the digital software structure used to control the rate parameter for the deposition of thin film devices. A synopsis of each module is presented in Table I.

As previously indicated, initial data has to be input to the algorithm prior to execution of the digital controller; see user example in Appendix D. Table II presents a complete listing of all the variables which must be initialized along with the variables which can be polled for deposition status. For example, if it is desired to know how long the process has been in the soak mode, polling the processor and inputting "PRINT CST" would result in a printout of the time in seconds that the soak routine has been executing.

All the modules used to perform the digital control of the deposition process have been defined. In order to perform the statistical analysis exactly as that used in the monitoring phase, a separate support software package, Appendix C, was developed in the BASIC programming language. The package completes the analysis so that a basis now exists for comparison between the analog and digital controller.

TABLE I

DIGITAL CONTROLLER'S SOFTWARE MODULE
AND FUNCTIONS PERFORMED BY EACH

MAIN:	Sets Channel on Crossbar Scanner Encodes DMM to take Voltage Reading Writes Termination Message on Deposition Completion
KEYIN:	Interprets Commands from Teletype Prints Response to Teletype on Command
CKI:	Transfer Control to Proper Routine on Clock Interrupt
TRAP HANDLER:	Services Software Trap Instructions
RISE:	Calculates Rise Increment Steps D/A Each Second Passes Control to Soak Routine
SOAK:	Maintains D/A at Final Rise Value Counts Seconds for Execution Passes Control to Deposition Routine
DEPOS:	Obtains Freq Value Calculates Rate Value Calls APPASX Routine Compare D/A Value for Max/Min Assigns Multiplexer Channels Sets D/A Values Commands Punch Routines
APPASX:	Calculates Rate Error from Rate Value Calculates Controller Output
ADD:	Stores D/A Values Between Samples Sets Max/Min D/A Values
DACQ:	Controls Multiplex Values for DMM Command Measurements Converts BCD to 3 Word Flt. Pt.
CTLMDX:	Controls Multiplexer Status
POWER FAIL:	Stores Working Register on Power Loss Resets Hardware to Status Prior to Power Loss on Power Up Restores Working Registers on Power Up
DEBUG:	Conversational Interface with Machine Language Sets Sample Time

TABLE II

VARIABLE LIST FOR DIGITAL CONTROLLER SOFTWARE

Variable	Definition
Rate Set	Desired Rate Value
Rate	Current Rate During Execution
Initial Rise	Initial Rise Input Value
Final Rise	Final Rise Input Value
Rise Time	Rise Time Desired in Seconds
Soak Time	Soak Time Desired in Seconds
Deposit Time	Deposit Time Desired in Seconds
Thickness	Desired Termination Frequency
Max Power	Maximum Increment D/A Can Be Increased
Min Power	Minimum Increment D/A Can Be Decreased
B2	Velocity Term
Punch On	Activates Punch Routine
Deposit	Initiates DEPOS Routine
CRT	Current Rise Time
CST	Current Soak Time
CDT	Current Deposit Time
Go	Starts Controller Processing
X	Emergency Stops

Chapter 6

CONTROLLER OPTIMIZATION

Experiments were performed holding the velocity multiplier, W, at a constant value while varying the sample time of the controller. These experiments demonstrated not only a sensitivity of the controller to the variation of the velocity multiplier, but also to sample time variations. A series of experiments to step each of the variables were conducted in order to establish the optimal velocity multiplier and sample time for the digital controller. The matrix of deposition runs used to systematically evaluate the variables is illustrated in Fig. 6.1. For each material, the matrix is executed for the common deposition rates of one, five, and ten Hertz/sec. It is quite evident that the number of test runs, forty-five for the three rates, would become quite enormous if a large number of materials were investigated.

Based on the need to have a digital controller capable of depositing a wide range of materials, two materials, silver and tin selenide, each having widely different deposition characteristics were used. Thus, a total of ninety deposition runs, assuming one run per matrix point, had to be made to gather sufficient data to allow determination of the parameter values needed for optimal performance.

The basis of comparison for the parameters was the statistical analysis routine presented in Chapter 3. The validity of a single

Velocity Mult. / Sample Time	1	2	3	4	5
1	X	X	X	X	X
4	X	X	X	X	X
7	X	X	X	X	X

Figure 6.1. Variable Matrix For Digital Deposition Controller

run per matrix point seems questionable as a basis for comparison. If for a particular matrix point the statistical parameters indicate a given value, was the value due to a system perturbation of the affect of the matrix parameters? In order to answer the question, multiple runs per matrix point were included in the test sequence. Then the statistical mean of the parameter for multiple runs gave good indications of the performance of the matrix point.

The next concern was the determination of the number of runs per matrix point needed to have confidence that the statistical analysis does represent a true value. Ideally, a large number of runs, per matrix point, would give an adequate indication of the matrix value but would be impractical. It can be assumed that, for a large number of experiments, the statistical parameters, i.e., mean rate and standard deviation, can be represented by a normal distribution or in the case of a small number of samples approximated by the t-distribution. The second assumption to consider is that a ninety percent (90%) confidence interval for the true value of the statistical parameters can be adequately defined based on the data taken.

Hayslett [14] established a technique to determine the interval in which the true statistical parameter was bounded. In order to calculate the upper and lower range in which the true value of the statistical parameter can be expected to be found, the following relationship is to be used:

$$\mu_u = \overline{x} + t_{\alpha/2}(*s/\sqrt{n}) \tag{6.1}$$

and

$$\mu_L = \overline{x} - t_{\alpha/2}(*s/\sqrt{n}) \tag{6.2}$$

Where μ_u = the upper confidence limit,

μ_L = the lower confidence limit,

$\overline{x}$ = the measured mean value of the sampled data,

$t_{\alpha/2}$ = the t-distribution for given confidence level,

α = (1-confidence level),

s = the measured standard deviation of the sample data, and

n = the sample number.

Initially, estimations for a sample size indicated that three samples per matrix point might suffice as a true indication of statistical measure. Using the standard deviation of the rate data about the statistical mean as the parameter of interest, several matrix points were run for each of three chosen rates. Table III shows the results along with the interval in which the true standard deviation would be contained. As can be seen, the values of the interval appear to be close to the measured value. Thus, the choice of three samples per matrix point was accepted as sufficient.

With the criterion established that three or more samples would suffice to describe a matrix point, a set of data containing two hundred and forty (240) seconds was taken for each matrix point at each of the desired rates for both silver and tin selenide. A time interval of two hundred and forty seconds was chosen as a satisfactory control interval for two reasons: (1) the matrix size restriction in the support software and (2) the adequacy of the information gathered.

As indicated in Chapter 5, support software to plot and analyze the data acquired during the process control was written in BASIC. Ease of data manipulation made it advantageous to input all the data into the processor and let the routine call for it when desired. BASIC has a

TABLE III

SAMPLE OF RUNS TO SHOW INDICATION TRUE STATISTICAL PARAMETER

Rate	Velocity Multiplier	Sample Time	Mean of Parameter	Standard Deviation of Parameter	Interval ± Mean
1	4	1	.21	.04	.07
5	2	4	.37	.02	.03
10	4	1	.51	.11	.19
10	2	4	.60	.05	.08
10	2	7	1.04	.02	.03
5	3	1	.47	.02	.04

maximum matrix size restriction of 256 elements, thus the matrix size restrictions. Since the analog controller had always been able to establish control within four minutes, 240 seconds, it was felt that if the digital controller was to be an improvement over the analog controller, it should also be able to gain control within four minutes. Thus, the justification for the 240 seconds time interval for each run.

Since statistical data, especially the mean and the standard deviation, have meaning only if the sampled data can be considered to be random and can vary as a normal distribution, Appendix E demonstrates that the rate variable data do satisfy these criterion. Having also shown that three or more samples per matrix are sufficient to define the influence of that point on the controller's sensitivity, the test runs for the matrix points were completed. The statistical standard deviation parameter for the several runs at each matrix point has to be "massaged" to obtain the average and the standard deviation. The standard deviation of the rate data was chosen as the parameter of interest for evaluation because it gave the best measuring tool.

Averaging the several runs at each matrix point and recording the results, a completed matrix for a given material and rate, as shown in Fig. 6.2, can be obtained for analysis. To circumvent the numerical analysis task involved with the six separate matrices of fifteen points each, the data were plotted in a series of graphs, Appendix E. This permitted a quick analysis and a choice of optimum variables to be made. From an investigation of the graph, Fig. 6.3, a trend can be deduced for the material. As shown in the figure, the value of the mean of the standard deviation appeared to be the lowest for a velocity multiplier of four for all sample times. Analysis of the other data in Appendix F

Velocity Mult. / Sample Time	1	2	3	4	5
1	1.16	1.38	.81	.34	.80
4	1.14	.70	1.36	.44	.60
7	1.56	.54	.64	.58	.53

Figure 6.2. Variable Matrix for Digital Controlling a Silver Deposition at a Rate of Ten Hertz/Sec

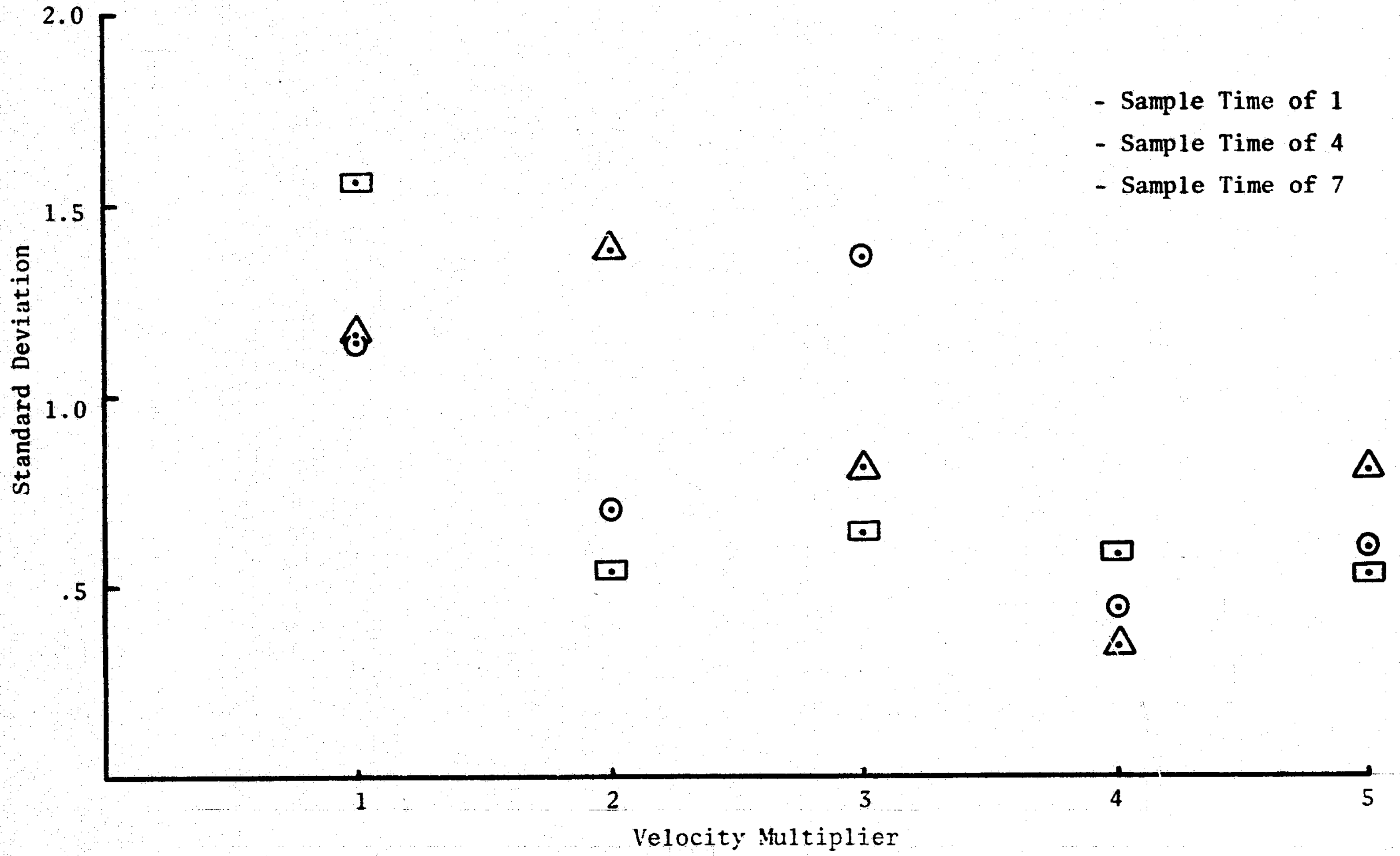


Figure 6.3. Standard Deviation versus Velocity Multiplier for Silver Deposition at Ten Hertz/Sec

yielded similar results. Thus, the conclusion was reached that a velocity multiplier of four appeared to give an optimal controller response. Further analysis of the data led to the conclusion that the choice of the sample time was not as straightforward as the choice of the velocity multiplier. For the data shown in the figure, it would appear that a sample time of one second would be the optimal choice. However, in order to obtain a set of parameters for each material, independent of the rate, all the rate data had to be investigated.

For silver, the data for the lower rates indicated a sample time of four seconds yielded the best result. Examining the individual deposition plots for the two sample times in question, a decision to choose the sample time of four seconds was made. Conducting a similar analysis for tin selenide yielded a result of a one second sample time for optimal response.

Table IV indicates the final results of the experimental testing which gave values for the unknown parameters established in Chapter 4. Using the results of the table, a series of twenty-five runs per rate per material was made in order to evaluate the optimal digital controller versus the analog controller.

This chapter has established the tuning procedure used to obtain the values of the unknown variables in the controller equations. In the following chapter, the analysis of the chosen controller for each material will be conducted.

TABLE IV

PARAMETER VALUES FOR THE OPTIMAL DIGITAL CONTROLLER

	Velocity Multiplier	Sample Time
Silver	4	4
Tin Selenide	4	1

Chapter 7

ANALYSIS OF OPTIMIZED DIGITAL CONTROLLER

This chapter will analyze the results achieved with the optimized digital controller and compare it with the optimized analog controller. Using the sample times and velocity multipliers established in Chapter 6 for silver and tin selenide, a series of twenty-five depositions at the most common rates were made. A similar series of depositions were conducted with the analog controller in order to obtain a basis for comparison.

A statistical analysis of each of the deposition runs yielded a mean rate value and a standard deviation about the mean. A statistical analysis of the mean rate values for the series of depositions yielded a mean expected rate value, $\overline{R}$, and a standard deviation about this mean, $S_{\overline{R}}$. Similarly, an analysis of the standard deviation of the rate variable about the mean for each run in a series resulted in a mean value for the standard deviation, $\overline{SD}$, and a standard deviation about this mean, $S_{\overline{SD}}$. Table V illustrates the results for both the digital and analog controller for the two materials at the common rates. It is advantageous to plot the data in Table V, to better illustrate the contrast between the two controllers. By normalizing the mean about the zero axis and the peak of the normal distribution function to one, the data can be collectively illustrated as a function of $\overline{SD}$.

TABLE V

RESULTS OF DIGITAL/ANALOG CONTROLLERS AT OPTIMAL SETTING

Material	Controller	Commanded Rate (Hz/sec)	Mean Rate ($\overline{R}$)	Stand. Deviation of Mean Rate ($S_{\overline{R}}$)	Mean Stand. Deviation ($\overline{SD}$)	Stand. Deviation of $\overline{SD}$ ($S_{\overline{SD}}$)
Silver	Digital	5	4.49	.10	.47	.15
Silver	Digital	10	9.58	.28	.43	.09
Silver	Analog	10	14.25	.20	1.73	1.74
Tin Selenide	Digital	5	4.48	.04	.35	.09
Tin Selenide	Digital	10	9.46	.09	.56	.11
Tin Selenide	Analog	5	4.65	.56	2.33	1.22
Tin Selenide	Analog	10	8.31	.70	1.96	.85

Setting the mean, μ, to zero and the standard deviation, σ, to the various values for $\overline{SD}$, a normal distribution function, f(x), using (7.1) can be calculated as the mean rate is varied from the zero axis.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-1/2\left(\frac{\mu - x}{\sigma}\right)^2} \qquad (7.1)$$

f(x) = distribution of the rate values about the mean

μ = mean rate

σ = standard deviation

Normalizing the peaks of the distribution functions to one, a series of graphs, Fig. 7.1, which illustrates the distribution of the deposition rate variable about the mean can be generated.

As an example, the $\overline{SD}$ for silver deposited at a rate of 10 Hz/sec is .43 with a mean of 9.58 Hz/sec. This indicates that the deposition rate variable can be expected to be within an interval of .215 Hz/sec about the mean. Thus a relative measure of the effectiveness of the controller can be seen.

As seen, a marked improvement over the analog controller can be expected from the digital controller. The expected standard deviation about the desired mean is quite small for the digital controller as compared to that for the analog controller.

Using Table V and (7.2) an indication of the controllability for the digital controller can be defined for a given material at a given rate.

$$CF \equiv \overline{SD}/2 \qquad (7.2)$$

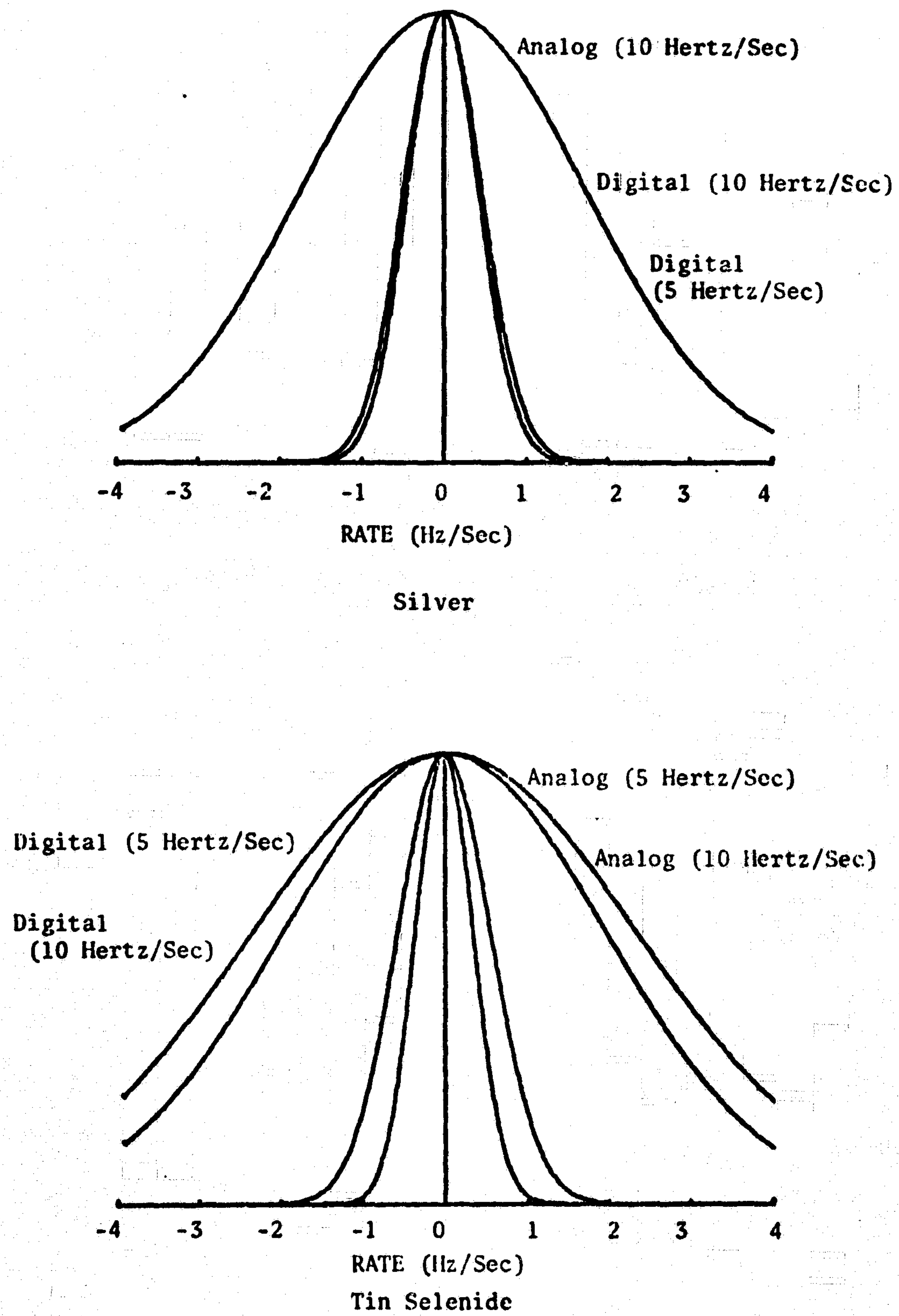


Figure 7.1. Normalized Distribution Curves for Silver/Tin Selenide Deposition with Optimized Digital Controller

Thus, the controllability factor, CF, is the interval spanned by one half the mean value of the standard deviation. For example, at a deposition rate of 10 Hz/sec the table yields an expected standard deviation of .43 Hz/sec and a CF of .215 for silver. Thus, the actual deposition rate variable could be expected to vary from 9.79 Hz/sec to 10.21 Hz/sec for a commanded rate of 10 Hz/sec. This translates to a deposition rate between 1.10 Å/sec and 1.15 Å/sec or a controllability factor of approximately .024 Å/sec control. Similar analysis for the tin selenide yields a controllability for the digital controller of approximately .1 Å/sec.

A measure of reproducibility for thin film devices produced with the digital controller can also be projected from Table V. From the information in the table, a numerical indication of the reproducibility factor, RF, for a given material and rate can be calculated using

$$RF = 3(S_{\overline{R}} + S_{\overline{SD}}) + \overline{SD}. \tag{7.3}$$

The factor of three in (7.3) represents three standard deviations which assure the spread needed to cover the majority of deposition rates.

This relationship can best be illustrated by the graph in Fig. 7.2. For any deposition run the mean rate is defined to be $\overline{R}$. Three times $S_{\overline{R}}$ gives the interval within which the mean rate is expected to be contained. Assuming that the mean rate occurred at either end of the interval, the mean standard deviation ($\overline{SD}$) will give the interval on either side of the mean rate about which the actual rate variable can be expected to fluctuate. Three times $S_{\overline{SD}}$ will include the total interval in which the deposition rate variable should be found. Thus, the deposition rate variable should always be found within the limits

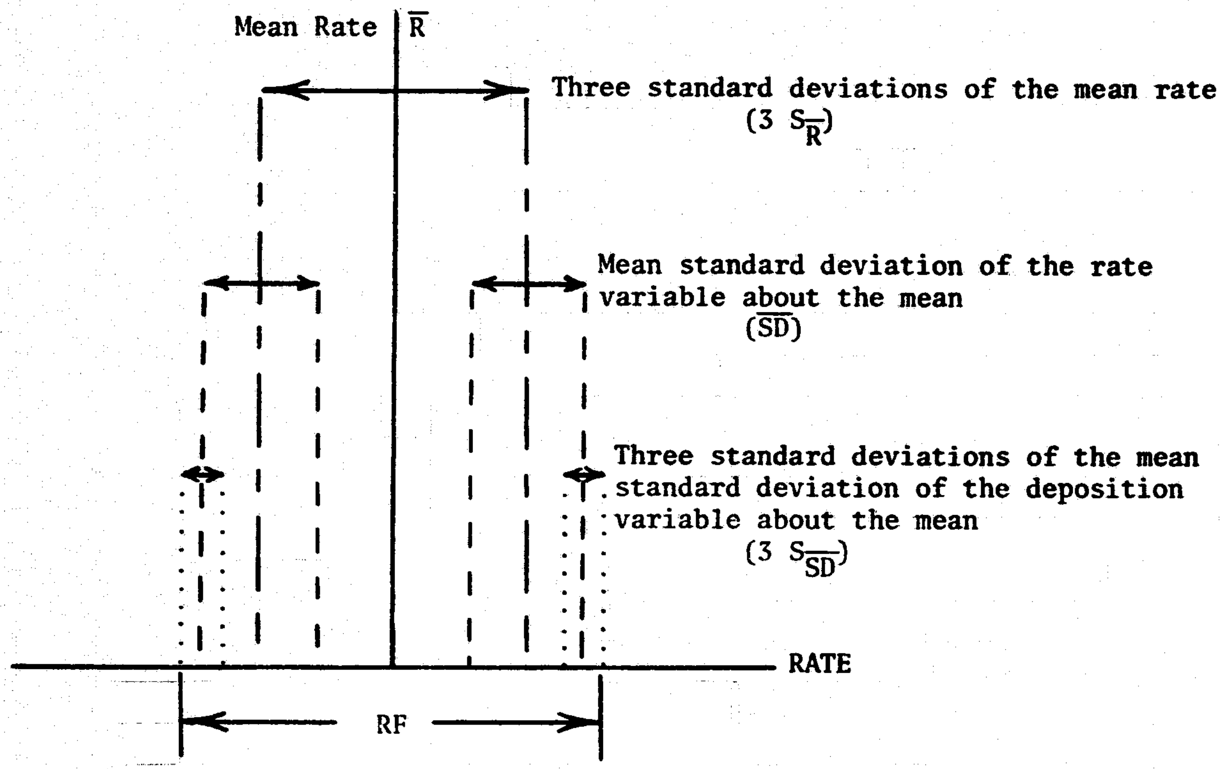


Figure 7.2. Graphical Illustration of the Reproducibility Factor for a Thin Film Deposition Controller

established by the reproducibility factor and over which the smaller the value RF, the smaller the interval the deposition rate variable should fluctuate.

Table VI illustrates both the controllability factors and the reproducibility factors measured with the analog and digital deposition controllers. As can be seen, the digital controller demonstrated superior results for both factors. To illustrate the response contrast of the analog and digital controllers, Fig. 7.3 depicts a deposition controlled by the analog controller and a digitally controlled deposition for the same material and rate. Shown in the figure, the digital controller achieves steady state response faster and with less overshoot than the analog controller.

To better illustrate typical responses of the digital controller, Fig. 7.4 shows a deposition run for both tin selenide and silver. As shown, both responses had achieved steady state in less than 45 seconds after the start of the deposition. It can be seen that the silver deposition had a slight overshoot. This can be attributed to two factors. One, the initial higher control setting was held longer than optimally required due to the longer sample time. Secondly, the lower than desired controller output at the completion of the soak phase resulted in a larger turn on power to achieve a rate. If the output at the completion of the soak phase had been nearest the power setting required to achieve the desired rate, the overshoot experienced with the longer sample time would have been minimal.

The longer sample time does offer an advantage in that part of the noise measured in the rate signal is filtered out. Thus, smaller changes are applied to the controller output. This response

TABLE VI

CONTROLLABILITY AND REPRODUCIBILITY FACTOR FOR DIGITAL/ANALOG CONTROLLERS AT OPTIMAL SETTINGS

Material	Controller	Commanded Rate (Hz/sec)	Controllability Factor (CF) (Hz/sec)	Reproducibility Factor (RF) (Hz/sec)
Silver	Digital	5	.24	1.22
Silver	Digital	10	.22	1.54
Silver	Analog	10	.87	7.55
Tin Selenide	Digital	5	.18	.74
Tin Selenide	Digital	10	.28	1.16
Tin Selenide	Analog	5	1.17	7.67
Tin Selenide	Analog	10	.98	6.61

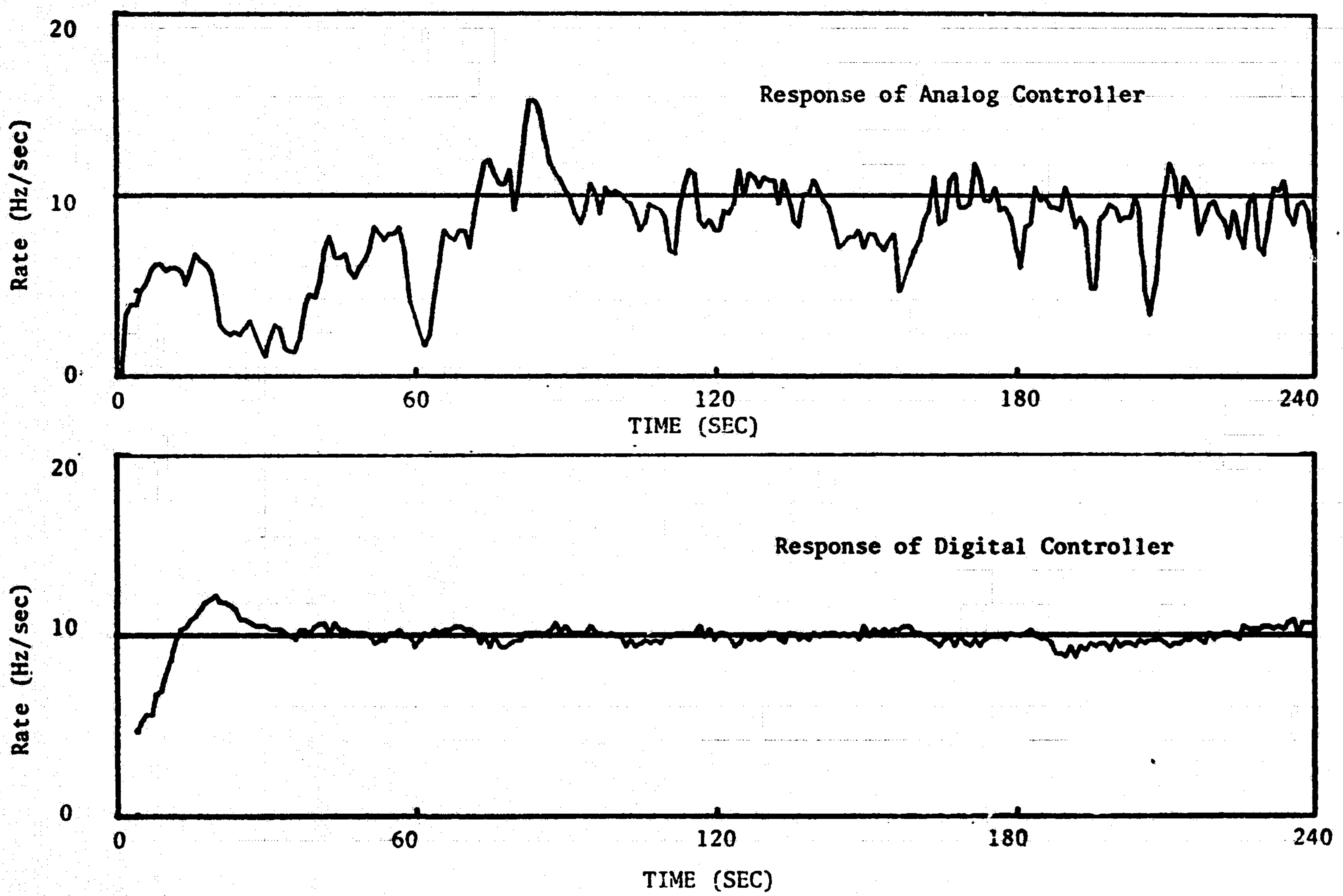
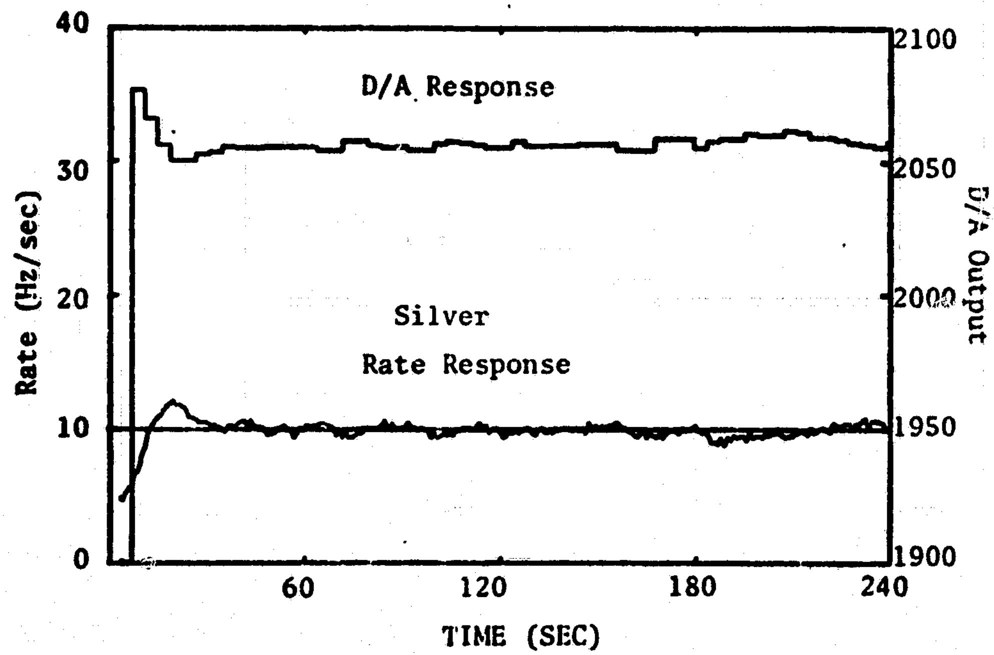


Figure 7.3. Analog-versus-Digital Controller Responses For Tin Selenide at a Deposition Rate of 10 Hz/sec



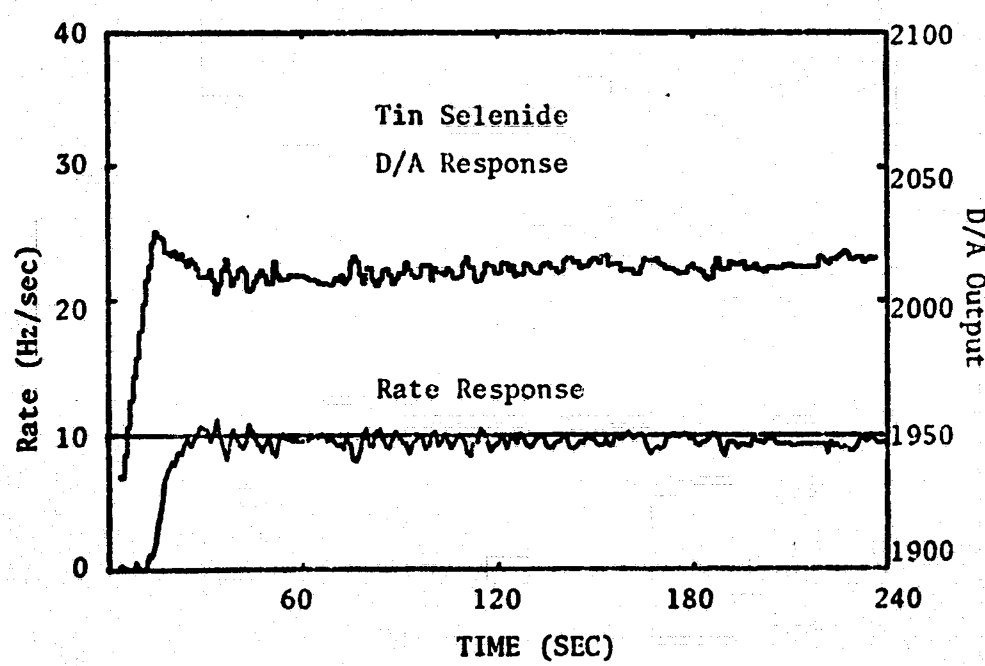


Figure 7.4. Typical Digitally Controlled Depositions

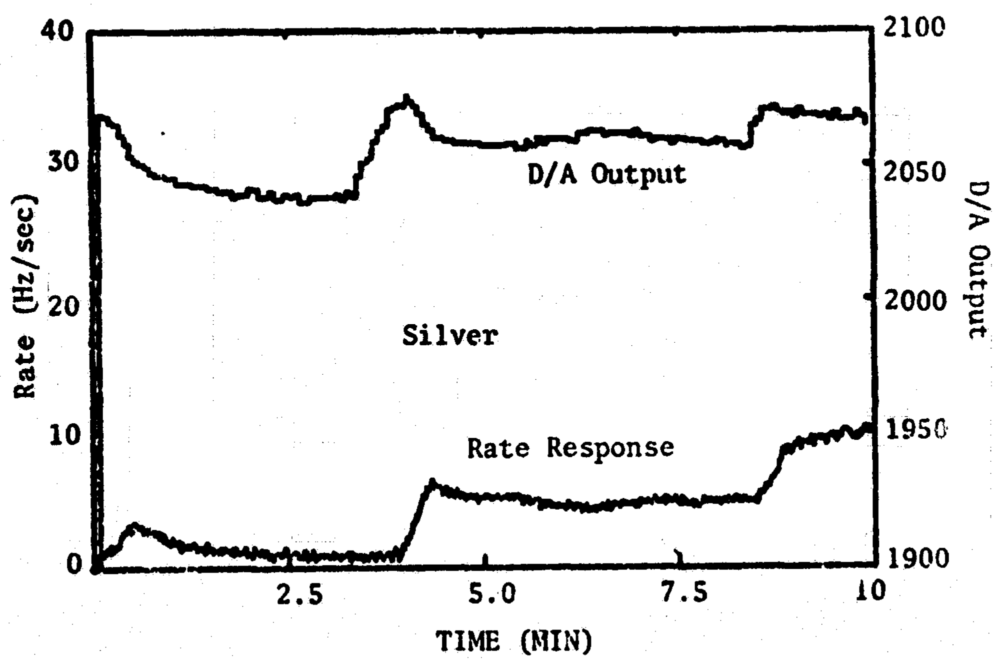
characteristic is also useful when a crystal snap occurs as will be introduced later in the chapter.

The shorter sample time used for the tin selenide resulted in minimal overshoot due to the rapid monitoring and updating of the controller output. As seen, the controller output peaked and began to cut back on the output before the rate response achieved the desired level. This illustrated the lead phase property or the desired anticipation of the controller to the response of the rate.

Illustrating the controller's dynamic capability, Fig. 7.5 shows the responses achieved with the digital controller for both tin selenide and silver during a deposition process containing the three rates of one, five, and ten Hz/sec, respectively. Observing that for silver and relative overshoots at the change of the rates are not as great as the initial overshoot, the effect of the power setting at the beginning of the process can be illustrated.

The overshoot problem can be reduced by either of two techniques. One, a software modification that slowly brings the soak power setting to a level that initiates a slow rise and then reduces the power. Second, a hardware modification could be made so as to locate the crystal detector under a shutter mechanism. This would shield the device until a steady rate had been attained.

Figure 7.6 illustrates the manner in which the digital controller reacts to a crystal snap. Many times the snap is not even sensed, especially on the longer sample times, due to the snap occurring between samples. Even if the controller senses the snap, the minimum limiter setting for the controller output eliminates the electron gun being turned completely off as was the case in the example shown in Fig. 1.1.



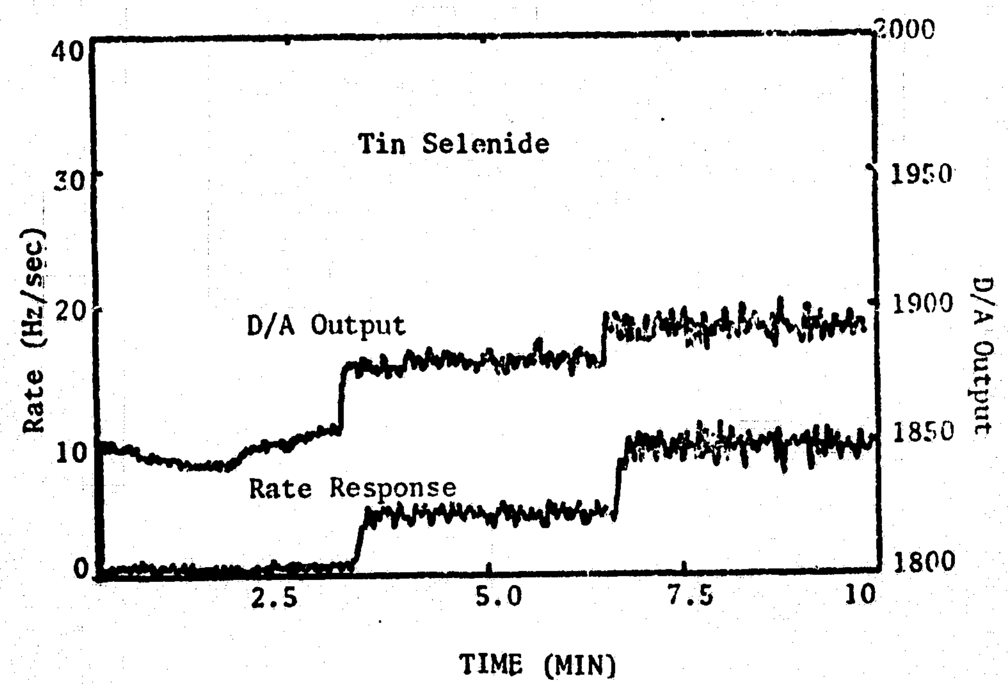


Figure 7.5. Dynamic Response Capability of Digital Controller

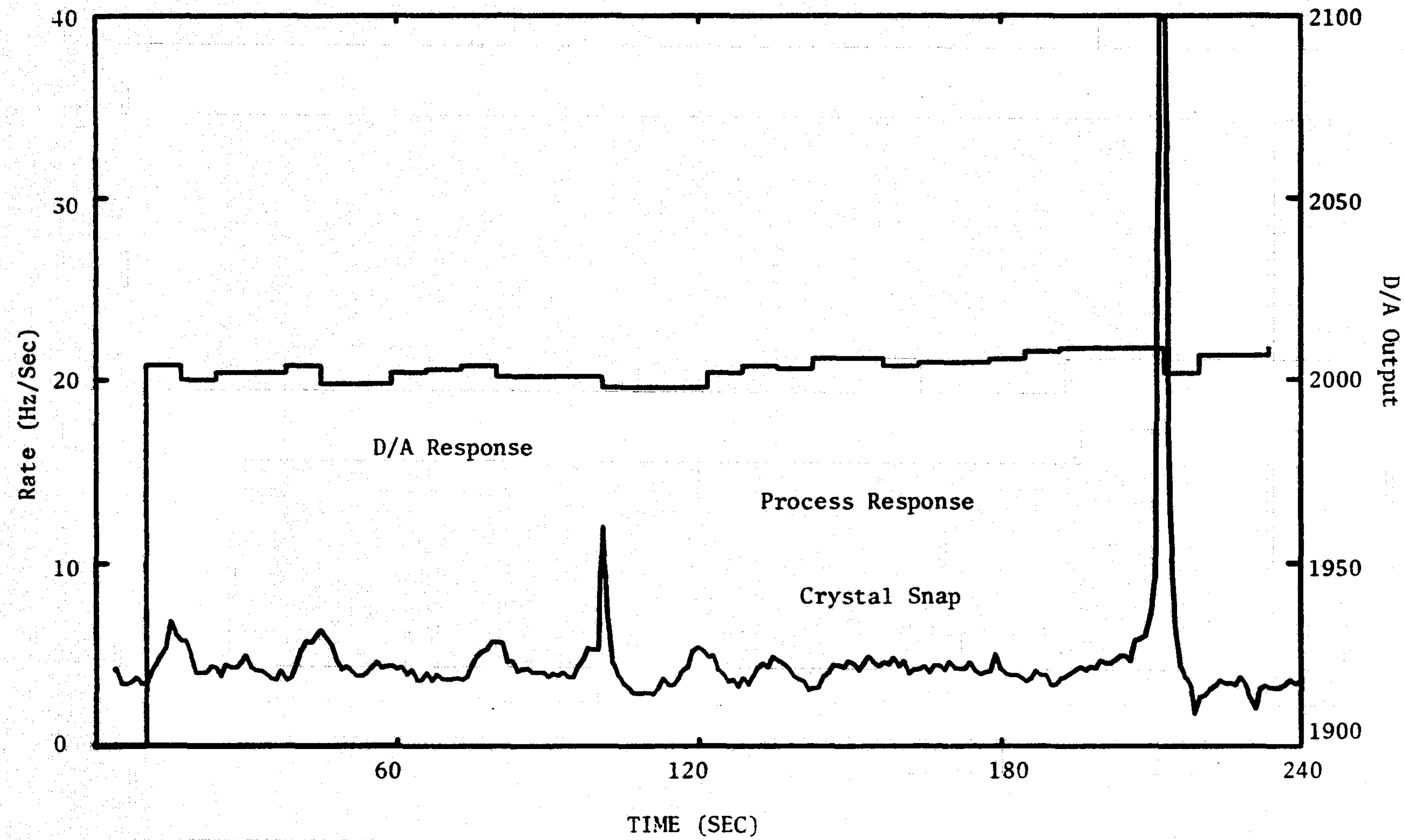


Figure 7.6. Illustration of Crystal Snap Response of Digital Controller

When the digital controller does sense the snap, the recovery time is seconds as compared to the forty-five seconds or more experienced with the analog controller. Not only is the effect on the controller output minimum, the overall effect to the rate of deposition is held to a minimum. As illustrated in Fig. 1.1, the rate went to near zero. When it did come back up, the overshoots and transient were enough to possibly effect the characteristics of the device being manufactured. Thus, it is desirable to have the snaps filtered out and their effect held to a minimal during the fabrication of the thin film devices.

Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

This dissertation has described a digital controller that controls the thin film deposition rate parameter. This chapter will summarize the conclusions of the effort and suggest recommendations for future work that might improve the system further.

A design criteria for a digital control system along with the hardware and software requirements has been described in this dissertation. A comparative analysis of data gathered using both the analog and digital controller has resulted in the conclusion that the digital deposition rate controller offers many advantages over the analog rate controller. To sum up these advantages, Table VII gives a composite comparison of the two controllers. It might be noted that some of the parameters in the table are expressed in terms of $\text{Å}/\text{sec}^2$ versus the Hz/sec previously defined. The values were obtained by using the conversion factor obtained in Chapter 3. The purpose of changing units was to contrast between the materials and the controllers and to establish continuity between the control terminology and the physical terminology.

The completion of the task has resulted in a digital thin film deposition controller whose characteristics exceed those of any known deposition controllers on the commercial market. A control method has been developed that allows the researcher to concentrate on the effect

TABLE VII

COMPARISON OF DIGITAL VERSUS ANALOG THIN FILM DEPOSITION CONTROLLERS

	Digital	Analog
Rise Time	65000 sec	180 sec
Soak Time	65000 sec	180 sec
Response Time to Steady State	< 45 sec	≈60 sec
Recovery from Crystal Snap	< 10 sec	≈45 sec
Controllability Factor	.02 Å/sec^2* (.05 Å/sec^2)**	.1 Å/sec^2 (.2 Å/sec^2)
Reproducibility Factor (Total Rate Spread)	.17 Å/sec^2* (.23 Å/sec^2)**	.9 Å/sec^2 (1.29 Å/sec^2)
Mean Standard Deviation about the Desired Rate	.05 Å/sec^2* (.11 Å/sec^2)**	.2 Å/sec^2 (.38 Å/sec^2)
Deposition Termination Factor	Time/Thickness	Thickness
Permanent Record of Deposition Parameter (PLOTS)	Yes	No
Statistical Analysis of Deposition Parameters	Yes	No
Deposition Parameter Data in Permanent Format (Paper Tape)	Yes	No
Deposition Parameter Input Format	TTY (conversational)	Interactive-Potentiometers
Ability to Real Time Monitor Control Parameters (Rise Time, Soak Time, Deposition Time, etc.)	Yes	No

* Parameter values for silver at a deposition rate of 1.0 Å/sec

** Parameter Values for tin selenide at a deposition rate of 2.0 Å/sec of parameters other than rate control on device characteristics. Thus, the objectives established in Chapter 1 have been met. It therefore appears that the use of a digital controller for thin film deposition should result in better thin film devices than could be obtained with an analog controller.

SUGGESTED FUTURE WORK

It is recommended that this work be continued by investigating the values of the sample time and velocity multipliers for other materials. Also, the investigation of using the control technique coupled with the work [15] to determine the possibility of reducing the hardware requirements is suggested.

Additional software routines to better achieve a soak power sufficiently close to the deposition power would enhance the capabilities of the controller software package. The incorporation of the routines to allow real time plotting of rate data along with statistical analysis would also be desirable improvements to the software package.

Hardware modification to include a processor controlled shutter between the crystal detector and the substrate would improve the system. This would allow filtering the initial transients and achieving steady state before opening the shutter. In a similar manner, the processor could close the shutter at the termination of a deposition. Thus, insuring that residual evaporation would not affect the thin film device being fabricated.

Augmentation of the system with another D/A and proper set of software to control the switching process could result in a system capable not only of co-deposition but also make possible the control of depositions in two separate vacuum chambers. Further modification of the software could result in a package to separately control two vacuum depositions independently while using a common set of software. Ultimately, an interactive software routine coupled with the BASIC conversational language could be developed which operated as a time sharing between the deposition process while performing user requested calculations.

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APPENDICES

APPENDIX A

The following computer program written in BASIC was used to conduct the monitoring phase of the research effort. This program has the capability of monitoring the deposition parameters at one second intervals during a deposition run under analog control. At the end of the monitoring mode, the software is capable of plotting the SCR and deposition rate parameters, conducting a statistical analysis on rate data, printing a label for the plot with pertinent deposition information, or punching the data on the High Speed Punch for permanent paper tape storage.

```
01 REM PROGRAM TO MONITOR & DATA ANALYSIS FROM DEPOSITION
02 REM OPTIONS REQUIRED -- 2,H,R,S,X,1,F,Q,T
03 REM...REVISED: OCTOBER 31,1973
04 GOTO 10
05 FOR N8=1 TO G0
06 LETU=EXF(17):LET U=EXF(11,N8+G0,2,7,21)
07 LET U=EXF(11,N8,2,4,20):LET U=EXF(20,1,N8)
08 NEXT N8
09 PRINT '':GOTO 30
10 PRINT 'MAX # OF MEASUREMENTS';:INPUT G0
11 LET U=EXF(20,2,G0)
12 PRINT 'FREQ METER - 3 OR 10 (KHZ)';:INPUT M2
13 PRINT 'MIN,MAX RATE SCALES';:INPUT R1,R2
14 PRINT 'MIN,MAX SCR SCALES';:INPUT S1,S2
15 IF M2=10 THEN 25
20 LET M=564.4567:LET B1=-5.40542:GOTO 30
25 LET M=1865.658:LET B1=-44.81548
30 REM
35 PRINT 'OPERATION:'
36 PRINT '1-PLOT(SCR), 2-STAT. ANAL., 3-PUNCH,'
38 PRINT '6-PLOT(RATE), 7-STOP, 8-LABEL, 9-MONITOR'
41 LET N8=EXF(21,1):LET G0=EXF(21,2)
42 IF N8<>0 THEN 45
43 PRINT 'INPUT ACTUAL # OF SAMPLES';:INPUT N8
44 LET U=EXF(20,1,N8)
45 INPUT O9
47 IF O9=9 THEN 900
48 IF O9=8 THEN 500
50 IF O9=7 THEN STOP
55 IF O9=6 THEN 200
70 IF O9=3 THEN 270
75 IF O9=2 THEN 335
80 IF O9=1 THEN 95
85 GOTO 30
95 PRINT 'INSTALL BLUE PEN...THEN CR';:INPUT A9
100 LET P1=S1:LET P2=S2
105 IF EXF(23)=16 GOTO 105
110 LET U=EXF(28,0,1,550,S2,S1,1,1,600,0)
130 GOTO 250
200 PRINT 'INSTALL BLACK PEN...THEN CR';:INPUT A9
205 LET P1=R1/M:LET P2=R2/M
210 IF EXF(23)=16 GOTO 210
215 LET U=EXF(28,1,551,1100,P2,P1,1,1,600,0)
250 GOTO 30
270 LET U=EXF(14,1,N8+G0)
275 GOTO 30
335 PRINT 'INPUT MIN AND MAX POINTS';:INPUT M8,M9
340 LET M8=M8+G0:LET M9=M9+G0
343 LET X1=(EXF(16,M9)-EXF(16,M8))/(M9-M8)
345 LET X=EXF(22,M8,M9,X1)
350 LET X1=X1*M
355 LET X=X/(M9-M8-1)
360 PRINT:PRINT:PRINT
```

```
365 PRINT "ANALYSIS COVERED POINTS ";M8-G0;" TO ";M9-G0
370 PRINT "STATISTICAL MEAN IS ";X1
375 PRINT "STATISTICAL STANDARD DEVIATION IS ";M*(X)^.5
380 PRINT "STATISTICAL VARIANCE IS ";M*M*X
385 PRINT:PRINT:PRINT:PRINT
390 GOTO 30
500 PRINT "DATE OF DEPOSTION...M,D,Y,#";:INPUT M1,D1,Y1,N1
505 PRINT"TYPE MATERIAL..KEY 1-QUARTZ,2-SILVER";
506 PRINT ",3-TINSELENIDE"
510 INPUT A8
515 PRINT"TYPE CONTROL..KEY 1-COMPUTER,2-SLOAN UNIT";
516 INPUT C1
520 LET S8=2
525 FOR I=1 TO 10:PRINT:NEXT I
530 PRINT "TEST DATE...";M1;"/";D1;"/";Y1;"#";N1
535 PRINT "DEPOSITION MATERIAL...";
540 IF A8=1 THEN PRINT "QUARTZ"
545 IF A8=2 THEN PRINT "SILVER"
550 IF A8=3 THEN PRINT "TIN SELENIDE"
565 PRINT "DEPOSITON MADE IN ";
575 IF S8=2 THEN PRINT "VARIAN ";
585 PRINT "VACUUM SYSTEM"
595 PRINT "DEPOSITON CONTROLLED BY THE ";
600 IF C1=1 THEN PRINT "COMPUTER"
605 IF C1=2 THEN PRINT "SLOAN UNIT"
610 PRINT:PRINT"                   SCALES"
615 PRINT "PEN COLOR","MIN","MAX","FCT"
620 FOR I=1 TO 48:PRINT "-";:NEXT I:PRINT
635 PRINT "   BLACK",R1,R2,"RATE"
638 PRINT "    BLUE",S1,S2,"SCR"
640 FOR I=1 TO 10:PRINT:NEXT I:GOTO 30
900 PRINT "<CR> WHEN READY TO MONITOR";:INPUT A9
905 GOTO 05
```

APPENDIX B

The following computer program modules written in Programmable Assembly Language (PAL) comprise the major portion of the software package to perform the digital controlling of the thin film deposition processing. The modules listed are coupled with other vendor supplied routines such as the Floating Point Math Package, Debug, and IOX. The software packages are presented in the following sequence with a brief synopcsis of each routine at its beginning:

MAIN
KEYIN
CKI
TRPHNP
RISE
SOAK
DEPOS
APPASX
ADD
DACQ
CTLMDX
POWER FAIL

MAIN

Sets Channel on Crossbar Scanner

Encodes DMM to take Voltage Readings

Writes Termination Message on Deposition Completion

```
                          ;
                          ; MAIN PROGRAM
                          ;
                          ; REV: 8/5/73
                          ;

                                  .GLOBL  START
                                  .GLOBL  DAQSUP,SENCDE,DAQEVL
                                  .GLOBL  FUNC,RANGE,CHAN,DACQ1,DACQ2,DACQ3,DACQ4
                                  .GLOBL  CTLMDX
                                  .GLOBL  CPFLAG,DTHFLG
                                  .GLOBL  C.X
        000000'                   .CSECT

                          ; REGISTER ASSIGNMENTS

        000000            R0      =       %0
        000001            R1      =       %1
        000002            R2      =       %2
        000003            R3      =       %3
        000004            R4      =       %4
        000005            R5      =       %5
        000006            SP      =       %6
        000007            PC      =       %7

        177776            PS      =       177776

                          ; IOX COMMAND CODES

        000001            INIC    =       1
        000002            RESEC   =       2
        000003            RSTRC   =       3
        000004            WAITC   =       4
        000005            SEEC    =       5
        000011            REAC    =       11
        000012            WRIC    =       12
```

```
        000013          REARC   =       13
        000014          WRIRC   =       14

                        ; IOX CALLS

        000004          INIT    =       IOT
        000004          RESETIOX=       IOT
        000004          RSTRT   =       IOT
        000004          WAITR   =       IOT
        000004          SEEK    =       IOT
        000004          READ    =       IOT
        000004          WRITE   =       IOT
        000004          READR   =       IOT
        000004          WRITR   =       IOT

        000000          DEV0    =       0
        177520          CKSR    =       177520
        177520          MDXCTL  =       177520
        177522          DMXOUT  =       177522

        000000          KBD     =       0
        000001          TTY     =       1
        000002          HSR     =       2
        000003          HSP     =       3

        104401          KEYIN   =       TRAP+1
        104400          IOWAIT  =       TRAP

        000340          PRIO7   =       340
        000015          CR      =       015
        000012          LF      =       012
```

```
000000  000000  000000              LIM:     .LIMIT
000004  000002                      FUN:     .WORD    2                ;VOLTAGE FUNCTION
000006  000004                      RNG:     .WORD    4                ;AUTO RANGE
000010  000025                      CHNL:    .WORD    21.              ;CHANNEL 21

000012  016706  177762              START:   MOV      LIM,SP   ;SET UP STACK
000016  005067  177776                       CLR      @#PS     ;RESET PRIORITY
000022  000004                               RESETIOX
000024  000000                               0
000026     002     000                       .BYTE    RESEC,0
000030  000004                               INIT
000032  000300                               HSPCDE
000034     001     003                       .BYTE    INIC,HSP
000036  012737  000004  177520               MOV      #4,@#MDXCTL      ;DEVICE 2
000044  012737  000003  177522               MOV      #3,@#DMXOUT      ;RESET OFF AT XBAR
000052  004767  000000G                      JSR      PC,C.X           ;TURN OFF FLAGS
000056  016767  177726  000000G              MOV      CHNL,CHAN        ;SET UP CHANNEL
000064  016767  177716  000000G              MOV      RNG,RANGE        ;SET UP RANGE
000072  016767  177706  000000G              MOV      FUN,FUNC         ;SET UP FUNCTION
000100  004767  000000G                      JSR      PC,DACEVL
000104  016767  000000G 000000G              MOV      DACQ1,DACQ3      ;TRANSFER ENCODED INFO
000112  016767  000000G 000000G              MOV      DACQ2,DACQ4
000120  004767  000000G                      JSR      PC,DACSUP        ;SET UP DATA ACQ.
000124  004767  000000G                      JSR      PC,SENCDE
000130  004567  000000G                      JSR      R5,CTLMDX
000134  010000                               DEV0
000136  052737  000100  177520               BIS      #100,@#CKSR      ;TURN ON CLOCK
000144  052737  000340  177776      WATLP:   BIS      #PRI07,@#PS
000152  005767  000000G                      TST      CPFLAG
000156  001407                               BEQ      WA.01
000160  005067  000000G                      CLR      CPFLAG
000164  042737  000340  177776               BIC      #PRI07,@#PS
000172  104401                               KEYIN
000174  000763                               BR       WATLP
000176  005767  000000G             WA.01:   TST      DTHFLG           ;IS DEPOSITION THROUGH?
000202  001412                               BEQ      WA.02
```

```
000204  042737  000340  177776          BIC     #PRIO7,@#PS
000212  104400                          IOWAIT
000214  000001                          TTY
000216  000004                          WRITE
000220  000242'                         DTBUF
000222     012     001                  .BYTE   WRIC,TTY
000224  005067  000000G                 CLR     DTHFLG
000230  042737  000340  177776  WA.02:  BIC     #PRIO7,@#PS
000236  000001                          WAIT
000240  000741                          BR      WATLP

000242  000030                  DTBUF:  DTBE-DTBS
000244  000000                          0
000246  000030                          DTBE-DTBS
000250     015     012          DTBS:   .BYTE   CR,LF
000252     104     105     120          .ASCII  /DEPOSITION COMPLETED/
000255     117     123     111
000260     124     111     117
000263     116     040     103
000266     117     115     120
000271     114     105     124
000274     105     104
000276     015     012                  .BYTE   CR,LF
000300                          DTBE:   .EVEN
000300  000006                  HSPCDE: .WORD   6

        000001'                         .END
```

KEYIN

Interprets Commands from Teletype

Prints Response to Teletype on Command

```
                        ; KEYIN
                        ;
                        ; REV: 8/4/73
                        ;
                                .TITLE  KEYIN
                                .GLOBL S.DA.TEMP.D.AMIN
                                .GLOBL  S.KEY.C.X

                                .GLOBL  NPF.TSEC.SEC.MIN.HR
                                .GLOBL  R.FIN.R.STRT.R.TIME.R.DA.R.SEC.RISFLG
                                .GLOBL  S.SEC.S.TIME.S.DA.SOKFLG
                                .GLOBL  D.TIME.D.SEC.D.M.D.O.CREF.D.FLIM
                                .GLOBL  D.DLO.D.DFLO.D.DHI.D.DFHI.DEPFLG.DTHFLG
                                .GLOBL  ALPHA.BETA.A1.A2.B1.B2.C1.C2.C3
                                .GLOBL  M1.M2.M3.CBAR1.CBAR2.CBAR3
                                .GLOBL  MBAR1.MBAR2.MBAR3.E1.E2.E3
                                .GLOBL  P2MM0.P2CC0.P2CM0.P1MM0.P1MM1.P1CC0
                                .GLOBL  P1CC1.P1CM0.P1CM1.P2CM1.P0CC1.P0CC2
                                .GLOBL  P0CM1.P0CM2.FLAST.PCHFLG.AUXFLG
                                .GLOBL  DATMP.RATE

                                .GLOBL  O.ENTR.CTLMDX

        000000          KBD     =       0
        000001          TTY     =       1
        000002          HSR     =       2
        000003          HSP     =       3

        104400          IOWAIT  =       TRAP

        000015          CR      =       015
        000012          LF      =       012

        177522          DACTL   =       177522
        000000          DFV0    =       0
```

```
                ; REGISTER ASSIGNMENTS
000000          R0      =       %0
000001          R1      =       %1
000002          R2      =       %2
000003          R3      =       %3
000004          R4      =       %4
000005          R5      =       %5
000006          SP      =       %6
000007          PC      =       %7

177776          PS      =       177776

                ; FPP-11 EMT CALLS

104001          ADDF    =       EMT+1
104002          SUBF    =       EMT+2
104004          MULF    =       EMT+4
104007          MOVF    =       EMT+7
104011          FIX     =       EMT+11
104013          FLT     =       EMT+13
104015          ITOA    =       EMT+15
104017          FTOA    =       EMT+17
104022          ATOI    =       EMT+22
104023          ATOF    =       EMT+23

000200          FAM     =       200
000100          PM      =       100

                ; IOX COMMAND CODES

000011          REAC    =       11
000012          WRIC    =       12
000013          REARC   =       13
000014          WRIRC   =       14
```

```
                        ; IOX CALLS

        000004          READ    =       IOT
        000004          WRITE   =       IOT
        000004          READR   =       IOT
        000004          WRITR   =       IOT
```

```
        000000'                          .CSECT

                                ; GET-NON-BLANK ROUTINE:
                                ; R1=BUFFER ↑, R2=END OF BUFFER ↑
                                ; ON RETURN V BIT CLEAR = R1 ↑ NEXT NON-BLANK/TAB
                                ;            V BIT SET = R1 ↑ END OF BUFFER

000000  020102                  GNB:     CMP     R1,R2             ;END OF BUFFER?
000002  103012                           BHIS    GNB.99            ;YES
000004  121127  000040                   CMPB    (R1),#040         ;BLANK?
000010  001002                           BNE     GNB.01            ;NO
000012  005201                  GNB.02:  INC     R1                ;TRY NEXT BYTE
000014  000771                           BR      GNB
000016  121127  000011          GNB.01:  CMPB    (R1),#011         ;TAB?
000022  001773                           BEQ     GNB.02            ;YES
000024  000242                           CLV                       ;NO--NON BLANK
000026  000207                           RTS     PC
000030  000262                  GNB.99:  SEV                       ;END OF BUFFER
000032  000207                           RTS     PC

                                ; SEARCH ROUTINE:
                                ; R1=BUFFER ↑, R2=END OF BUFFER ↑
                                ; R0=SEARCH PROTOTYPE LIST ↑
                                ; R3=LIST ITEM # * 2 IF MATCH FOUND, ELSE (R3)=-2
                                ; R4=INTERNAL LIST BYTE COUNTER
                                ; ON RETURN R1 POINTS TO BYTE AFTER ITEM FOUND OR TO
                                ; BYTE AFTER BUFFER END. R3 SET AS ABOVE.

000034  010146                  SRCH:    MOV     R1,-(SP)          ;SAVE ↑
000036  005003                           CLR     R3                ;RESET ITEM COUNTER
000040  112004                  SR.00:   MOVB    (R0)+,R4          ;GET ITEM LENGTH
000042  001416                           BEQ     SR.99             ;0=END OF LIST
000044  011601                           MOV     (SP),R1           ;START OF STRING
000046  004767  177726          SR.01:   JSR     PC,GNB            ;NEXT NON BLANK
000052  102412                           BVS     SR.99             ;NONE LEFT
000054  005304                           DEC     R4                ;COUNT THE BYTE
```

```
000056  122120                  CMPB    (R1)+,(R0)+     ;BUFFER:LIST
000060  001004                  BNE     SR.02           ;NO MATCH
000062  005704                  TST     R4              ;LIST ITEM END?
000064  003370                  BGT     SR.01           ;NO
000066  005726          SR.TN:  TST     (SP)+           ;POP OLD ↑
000070  000207                  RTS     PC
000072  005723          SR.02:  TST     (R3)+           ;ADD 2 TO ITEM CTR
000074  060400                  ADD     R4,R0           ;GO TO NEXT ITEM
000076  000760                  BR      SR.00
000100  012703  177776  SR.99:  MOV     #-2,R3          ;END OF LIST
000104  000770                  BR      SR.TN
```

```
000106                           S.KEY:                                  ;KEYIN
000106  004767  000002                   JSR     PC.KEY.00
000112  000002                           RTI
000114  104400                   KEY.00: IOWAIT
000116  000001                           TTY
000120  000004                           WRITR                           ;PROMPT WITH ":"
000122  002210'                          PROMPT
000124     014     001                   .BYTE   WRIRC.TTY
000126  000132'                          KEY.01
000130  000207                           RTS     PC
000132  104400                   KEY.01: IOWAIT
000134  000000                           KBD
000136  000004                           READR                           ;GET THE REPLY
000140  002234'                          KBUFF
000142     013     000                   .BYTE   REARC.KBD
000144  000150'                          KEY.02
000146  000207                           RTS     PC
000150  012701  002242'          KEY.02: MOV     #KBIN.R1                ;↑ BEGINNING OF BUFFER
000154  010102                           MOV     R1.R2
000156  066702  002056                   ADD     KBCT.R2                 ;↑ END OF BUFFER +1
000162  012700  000212'                  MOV     #CCLIST.R0              ;CONTROL COMMAND LIST
000166  004767  177642                   JSR     PC.SRCH                 ;FIND OUT WHAT HE WANTS
000172  000173  000262'                  JMP     @CCPOUT(R3)             ;JUMP TO PROPER HANDLER
000176  104400                   KEY.Q:  IOWAIT
000200  000001                           TTY
000202  000004                           WRITE                           ;TELL HIM: WHAT'S WRONG?
000204  002222'                          QUERY
000206     012     001                   .BYTE   WRIC.TTY
000210  000207                   C.NULL: RTS     PC

000212     001                   CCLIST: .BYTE   1                       ;STRING LENGTH
000213     130                           .ASCII  /X/                     ;STRING
000214     001                           .BYTE   1
000215     015                           .BYTE   CR
000216     002                           .BYTE   2
000217     107     117                   .ASCII  /GO/
```

```
000221   003                      .BYTE   3
000222   114   105   124          .ASCII  /LET/
000225   005                      .BYTE   5
000226   120   122   111          .ASCII  /PRINT/
000231   116   124
000233   005                      .BYTE   5
000234   120   125   116          .ASCII  /PUNCH/
000237   103   110
000241   007                      .BYTE   7
000242   104   105   120          .ASCII  /DEPOSIT/
000245   117   123   111
000250   124
000251   005                      .BYTE   5
000252   104   105   102          .ASCII  /DEBUG/
000255   125   107
000257   000                      .BYTE   0               ;END OF LIST
                                  .EVEN

000260   000176'                  KEY.Q                   ;ERROR ROUTINE
000262   000510'          CCROUT: C.X
000264   000213'                  C.NULL
000266   000302'                  C.GO
000270   000550'                  C.LET
000272   001550'                  C.PRNT
000274   002044'                  C.PNCH
000276   002146'                  C.DEPS
000300   000000G                  D.ENTR
```

```
000302                             C.GO:                              ;GO: START DEPOSITION
000302  052737  000340  177776            BIS     #340,@#PS
000310  012701  000370'                   MOV     #SIS,R1            ;START OF SWI LIST TO 0
000314  020127  000412'            CG.01: CMP     R1,#SIE2           ;END OF LIST?
000320  103002                            BHIS    CG.02              ;YES
000322  005031                            CLR     @(R1)+             ;NO. CLEAR THE SWI
000324  000773                            BR      CG.01
000326  012701  000412'            CG.02: MOV     #FPS,R1            ;START OF FPN LIST TO 0
000332  012702  000362'                   MOV     #F.0,R2            ;↑ FPN OF 0
000336  020127  000510'            CG.03: CMP     R1,#FPE            ;END OF LIST?
000342  103003                            BHIS    CG.04              ;YES
000344  104007                            MOVF
000346  011231                            MOV     (R2),@(R1)+        ;NO. CLEAR THE FPN
000350  000772                            BR      CG.03
000352  012767  177777  000000G    CG.04: MOV     #-1,RISFLG         ;TURN ON RISE
000360  000207                            RTS     PC

000362  000000  000000  000000     F.0:   .WORD   0,0,0

000370                             SIS:                       ;START OF SWI ↑ FOR 0'ING
000370  000000G                           RISFLG
000372  000000G                           SOKFLG
000374  000000G                           DEPFLG
000376  000000G                           DTHFLG
000400                             SIE1:                      ;END OF PART 1 - "X"
000400  000000G                           R.DA
000402  000000G                           R.SEC
000404  000000G                           S.SEC
000406  000000G                           D.SEC
000410  000000G                           TSEC
000412                             SIE2:                      ;END OF PART 2 - "GO"
000412                             FPS:                       ;START OF FPN ↑ FOR 0'ING
000412  000000G                           FLAST
000414  000000G                           D.FLIM
000416  000000G                           C1
000420  000000G                           C2
```

```
000422   000000G                              C3
000424   000000G                              M1
000426   000000G                              M2
000430   000000G                              M3
000432   000000G                              E1
000434   000000G                              E2
000436   000000G                              E3
000440   000000G                              CBAR1
000442   000000G                              CBAR2
000444   000000G                              CBAR3
000446   000000G                              MBAR1
000450   000000G                              MBAR2
000452   000000G                              MBAR3
000454   000000G                              P2MM0
000456   000000G                              P2CC0
000460   000000G                              P2CM0
000462   000000G                              P1MM0
000464   000000G                              P1MM1
000466   000000G                              P1CC0
000470   000000G                              P1CC1
000472   000000G                              P1CM0
000474   000000G                              P1CM1
000476   000000G                              P2CM1
000500   000000G                              P0CC1
000502   000000G                              P0CC2
000504   000000G                              P0CM1
000506   000000G                              P0CM2
000510                          FPE:                             ;END OF FPN ↑
```

```
000510                              C.X:                        ;X: STOP EXECUTION
000510  052737  000340  177776             BIS     #340,@#PS    ;LOCK ALL OUT!!
000516  012701  000370'                    MOV     #SIS,R1      ;START OF SWI·LIST TO 0
000522  020127  000400'             CX.01: CMP     R1,#SIE1     ;END OF LIST?
000526  103002                             BHIS    CX.02        ;YES
000530  005031                             CLR     @(R1)+       ;NO, CLEAR THE SWI
000532  000773                             BR      CX.01
000534  004567  000000G             CX.02: JSR     R5,CTLMDX
000540  000000                             DEV0                 ;D/A CONV.
000542  005037  177522                     CLR     @#DACTL
000546  000207                             RTS     PC
```

```
000550                              C.LET:                              ;LET: SET UP A VARIABLE
000550  012700  001056'                     MOV     #VARLIS,R0          ;PROTOTYPES
000554  004767  177254                      JSR     PC,SRCH             ;FIND A MATCH
000560  005703                              TST     R3                  ;MATCH?
000562  002002                              BGE     CL.01
000564  000167  177406              CL.00:  JMP     KEY.Q               ;SHOW ERROR
000570  004767  177204              CL.01:  JSR     PC,GNB              ;SKIP BLANKS
000574  102773                              BVS     CL.00               ;BR IF NONE
000576  122127  000075                      CMPB    (R1)+,#'=           ;LOOK FOR "="
000602  001372                              BNE     CL.01               ;NOT FOUND
000604  104023                              ATOF                        ;CONVERT TO FPN
000606  011167  000214                      MOV     (R1),FTEMP          ;FTEMP IS PLACE
000612  102764                              BVS     CL.00               ;ERROR
000614  000173  001342'                     JMP     @VROUT(R3)          ;GO TO HANDLER

000620  052737  000340  177776      CL.F:   BIS     #340,@#PS           ;LOCK OTHERS OUT
000626  104007                              MOVF                        ;MOVE # TO DST
000630  016773  000172  001276'             MOV     FTEMP,@VADR(R3)
000636  000207                              RTS     PC
000640  016773  000162  001276'     CL.I:   MOV     FTEMP,@VADR(R3)     ;MOVE SWI
000646  000207                              RTS     PC

000650                              CL.DA:                              ;SET UP A D/A DATUM
000650  104004                              MULF                        ;SCALE 0-999 TO 0-4095
000652  016767  000156  000146              MOV     F.C0,FTEMP          ;FTEMP*4095/999
000660  102002                              BVC     .+6
000662  005726                      CL.DA1: TST     (SP)+               ;POP RTN ADR
000664  000737                              BR      CL.00               ;ERROR
000666  104011                              FIX                         ;CONVERT TO INTEGER
000670  016767  000132  000130              MOV     FTEMP,FTEMP
000676  102771                              BVS     CL.DA1              ;ERROR
000700  026727  000122  007777              CMP     FTEMP,#4095.        ; & <= 4095
000706  003365                              BGT     CL.DA1
000710  000207                              RTS     PC

000712                              CL.PWR:                             ;LET A POWER SETTING
```

```
000712  004767  177732                    JSR     PC,CL.DA
000716  000750                            BR      CL.I                    ;STORE IT

000720                          CL.DST:                                   ;LET DEPOSITION POWER
000720  004767  177724                    JSR     PC,CL.DA
000724  052737  000340  177776            BIS     #340,@#PS               ;LOCK OUT ALL
000732  004767  177702                    JSR     PC,CL.I                 ;STASH SWI
000736  004767  001062                    JSR     PC,PATCH4
000742  026327  001276' 000000G           CMP     VADR(R3),#D.DLO         ;LOW LIMIT?
000750  001005                            BNE     CL.DS1                  ;NO
000752  104007                            MOVF                            ;YES
000754  016767  000046  000000G           MOV     FTEMP,D.DFLO
000762  000207                            RTS     PC
000764  104007                  CL.DS1:   MOVF                            ;SAVE HIGH LIMIT FPM
000766  016767  000034  000000G           MOV     FTEMP,D.DFHI
000774  000207                            RTS     PC

000776                          CL.TIM:                                   ;LET A TIME VALUE
000776  104011                            FIX                             ;DIRECTLY TO INT
001000  016767  000022  000020            MOV     FTEMP,FTEMP
001006  102666                            BVS     CL.00                   ;OVERFLOW
001010  100665                            BMI     CL.00                   ;NOT >=0
001012  000712                            BR      CL.I                    ;SAVE IT

001014                          CL.THK:                                   ;LET THICKNESS
001014  104001                            ADDF                            ;GET LAST FREQUENCY
001016  016767  000000G 000002            MOV     FLAST,FTEMP
001024  000675                            BR      CL.F                    ;STORE DIFFERENCE

001026  001034'                 FTEMP:    .=.+6
001034  164357  040625  100003  F.C0:     .WORD   164357,040625,100003        ;4095/999
001042  147175  076347  077776  F.C1:     .WORD   147175,076347,077776        ;999/4095
001050  000000  040000  100000  F.C2:     .WORD   0,040000,100000             ;.5
```

```
001056                                VARLIS:                          ;VARIABLE LIST
001056      011                                 .BYTE    9.
001057      106       111       116             .ASCII   /FINALRISE/
001062      101       114       122
001065      111       123       105
001070      013                                 .BYTE    11.
001071      111       116       111             .ASCII   /INITIALRISE/
001074      124       111       101
001077      114       122       111
001102      123       105
001104      010                                 .BYTE    8.
001105      122       111       123             .ASCII   /RISETIME/
001110      105       124       111
001113      115       105
001115      010                                 .BYTE    8.
001116      123       117       101             .ASCII   /SOAKTIME/
001121      113       124       111
001124      115       105
001126      011                                 .BYTE    9.
001127      123       117       101             .ASCII   /SOAKPOWER/
001132      113       120       117
001135      127       105       122
001140      013                                 .BYTE    11.
001141      104       105       120             .ASCII   /DEPOSITTIME/
001144      117       123       111
001147      124       124       111
001152      115       105
001154      011                                 .BYTE    9.
001155      106       122       105             .ASCII   /FREQSCALE/
001160      121       123       103
001163      101       114       105
001166      012                                 .BYTE    10.
001167      106       122       105             .ASCII   /FREQOFFSET/
001172      121       117       106
001175      106       123       105
001200      124
```

```
   001201     007                           .BYTE   7
   001202     122     101     124           .ASCII  /RATESET/
   001205     105     123     105
   001210     124
   001211     011                           .BYTE   9.
   001212     124     110     111           .ASCII  /THICKNESS/
   001215     103     113     116
   001220     105     123     123
   001223     010                           .BYTE   8.
   001224     115     111     116           .ASCII  /MINPOWER/
   001227     120     117     127
   001232     105     122
   001234     010                           .BYTE   8.
   001235     115     101     130           .ASCII  /MAXPOWER/
   001240     120     117     127
   001243     105     122
   001245     005                           .BYTE   5
   001246     101     114     120           .ASCII  /ALPHA/
   001251     110     101
   001253     004                           .BYTE   4
   001254     102     105     124           .ASCII  /BETA/
   001257     101
   001260     002                           .BYTE   2
   001261     101     061                   .ASCII  /A1/
   001263     002                           .BYTE   2
   001264     101     062                   .ASCII  /A2/
   001266     002                           .BYTE   2
   001267     102     061                   .ASCII  /B1/
   001271     002                           .BYTE   2
   001272     102     062                   .ASCII  /B2/
   001274     000                           .BYTE   0
                                            .EVEN
   001276                           VADR:                               ;ADDRESS OF VARIABLES
   001276   000000G                         R.FIN   ;FINAL RISE
   001300   000000G                         R.STRT  ;INITIAL RISE
   001302   000000G                         R.TIME  ;RISE TIME
```

```
001304  000000G                  S.TIME  ;SOAK TIME
001306  000000G                  S.DA    ;SOAK POWER
001310  000000G                  D.TIME  ;DEPOSIT TIME
001312  000000G                  D.M     ;FREQ SCALE
001314  000000G                  D.O     ;FREQ OFFSET
001316  000000G                  CREF    ;RATE SET
001320  000000G                  D.FLIM  ;THICKNESS
001322  000000G                  D.DLO   ;MIN POWER
001324  000000G                  D.DHI   ;MAX POWER
001326  000000G                  ALPHA
001330  000000G                  BETA
001332  000000G                  A1
001334  000000G                  A2
001336  000000G                  B1
001340  000000G                  B2

001342                   VROUT:                        ;LET HANDLERS
001342  000712'                  CL.PWR  ;FINAL RISE
001344  000712'                  CL.PWR  ;INITIAL RISE
001346  000776'                  CL.TIM  ;RISE TIME
001350  000776'                  CL.TIM  ;SOAK TIME
001352  000712'                  CL.PWR  ;SOAK POWER
001354  000776'                  CL.TIM  ;DEPOSIT TIME
001356  000620'                  CL.F    ;FREQ SCALE
001360  000620'                  CL.F    ;FREQ OFFSET
001362  000620'                  CL.F    ;RATE SET
001364  001014'                  CL.THK  ;THICKNESS
001366  000720'                  CL.DST  ;MIN POWER
001370  000720'                  CL.DST  ;MAX POWER
001372  000620'                  CL.F    ;ALPHA
001374  000620'                  CL.F    ;BETA
001376  000620'                  CL.F    ;A1
001400  000620'                  CL.F    ;A2
001402  000620'                  CL.F    ;B1
001404  000620'                  CL.F    ;B2
```

```
        001406  001566'                          CP.01                    ;ERROR JUMP
        001410                           VRT1:                            ;PRINT HANDLERS #1
        001410  001754'                          CP.PR    ;FINAL RISE
        001412  001754'                          CP.PR    ;INITIAL RISE
        001414  001604'                          CP.I     ;RISE TIME
        001416  001604'                          CP.I     ;SOAK TIME
        001420  001754'                          CP.PR    ;SOAK POWER
        001422  001604'                          CP.I     ;DEPOSIT TIME
        001424  001646'                          CP.F     ;FREQ SCALE
        001426  001646'                          CP.F     ;FREQ OFFSET
        001430  001646'                          CP.F     ;RATE SET
        001432  001646'                          CP.F     ;THICKNESS
        001434  001754'                          CP.PR    ;MIN POWER
        001436  001754'                          CP.PR    ;MAX POWER
        001440  001646'                          CP.F     ;ALPHA
        001442  001646'                          CP.F     ;BETA
        001444  001646'                          CP.F     ;A1
        001446  001646'                          CP.F     ;A2
        001450  001646'                          CP.F     ;B1
        001452  001646'                          CP.F     ;B2

        001454                           V2LIST:                          ;PRINT, PROTOTYPES #2
        001454      004                          .BYTE    4
        001455      122     101     124          .ASCII   /RATE/
        001460      105
        001461      003                          .BYTE    3
        001462      103     122     120          .ASCII   /CRP/
        001465      003                          .BYTE    3
        001466      103     123     120          .ASCII   /CSP/
        001471      003                          .BYTE    3
        001472      103     104     120          .ASCII   /CDP/
        001475      003                          .BYTE    3
        001476      103     122     124          .ASCII   /CRT/
        001501      003                          .BYTE    3
        001502      103     123     124          .ASCII   /CST/
```

```
    001505     003                                     .BYTE    3
    001506     103      104      124                   .ASCII   /CDT/
    001511     000                                     .BYTE    0

    001512                                   V2ADR:                                ;VARIABLE ADDRESSES
    001512  000000G                                    RATE
    001514  000000G                                    R.DA     ;CRP
    001516  000000G                                    S.DA     ;CSP
    001520  000000G                                    DATMP    ;CDP
    001522  000000G                                    R.SEC    ;CRT
    001524  000000G                                    S.SEC    ;CST
    001526  000000G                                    D.SEC    ;CDT

    001530  002020'                                    CP.00                       ;ERROR
    001532                                   VRT2:                                 ;PRINT HANDLERS #2
    001532  001720'                                    CP.F2    ;RATE
    001534  001744'                                    CP.PR2   ;CRP
    001536  001744'                                    CP.PR2   ;CSP
    001540  001744'                                    CP.PR2   ;CDP
    001542  001636'                                    CP.I2    ;CRT
    001544  001636'                                    CP.I2    ;CST
    001546  001636'                                    CP.I2    ;CDT
```

```
001550                              C.PRNT:                                 ;PRINT: VARIABLE VALUES
001550  010105                              MOV     R1,R5                   ;SAVE ^
001552  012700  001056'                     MOV     #VARLIS,R0              ;PROTOTYPES, PART 1
001556  004767  176252                      JSR     PC,SRCH                 ;FIND A MATCH
001562  000173  001410'                     JMP     @VRT1(R3)               ;GO TO HANDLER
001566  010501                      CP.01:  MOV     R5,R1                   ;RESTORE ^
001570  012700  001454'                     MOV     #V2LIST,R0              ;PROTOTYPES, PART 2
001574  004767  176234                      JSR     PC,SRCH                 ;FIND A MATCH
001600  000173  001532'                     JMP     @VRT2(R3)               ;GO TO HANDLER

001604  017367  001276' 177214      CP.I:   MOV     @VADR(R3),FTEMP         ;MOVE THE SWI

001612  104015                      CP.SWI: ITOA                            ;CONVERT TO ASCII
001614  016767  177206  000546              MOV     FTEMP,IBUFS
001622  104400                              IOWAIT
001624  000001                              TTY
001626  000004                              WRITE
001630  002362'                             IBUF
001632     012     001                      .BYTE   WRIC,TTY
001634  000207                              RTS     PC

001636  017367  001512' 177162      CP.I2:  MOV     @V2ADR(R3),FTEMP;GET SWI
001644  000762                              BR      CP.SWI                  ;PRINT IT

001646  013746  177776              CP.F:   MOV     @#PS,-(SP)              ;SAVE STATUS
001652  052737  000340  177776              BIS     #340,@#PS               ;LOCK OUT
001660  104007                              MOVF                            ;MOVE THE FPN
001662  017367  001276' 177136              MOV     @VADR(R3),FTEMP

001670  012637  177776              CP.FPN: MOV     (SP)+,@#PS              ;RESTORE STATUS
001674  104017                              FTOA
001676  016767  177124  000504              MOV     FTEMP,FBUFS
001704  104400                              IOWAIT
001706  000001                              TTY
001710  000004                              WRITE
001712  002402'                             FBUF
```

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```
001714     012    001                 .BYTE   WRIC,TTY
001716  000207                        RTS     PC

001720  013746  177776        CP.F2:  MOV     @#PS,-(SP)        ;SAVE STATUS
001724  052737  000340  177776        BIS     #340,@#PS
001732  104007                        MOVF                      ;MOVE FPN
001734  017367  001512' 177064        MOV     @V2ADR(R3),FTEMP
001742  000752                        BR      CP.FPN

001744                        CP.PR2:                           ;PRINT A DEP.PWR
001744  017367  001512' 177054        MOV     @V2ADR(R3),FTEMP;MOVE SWI
001752  000403                        BR      CP.P01

001754                        CP.PR:                            ;PRINT A DEP.PWR
001754  017367  001276' 177044        MOV     @VADR(R3),FTEMP ;MOVE SWI
001762  004767  000036        CP.P01: JSR     PC,PATCH4                 ;FLOAT THE NUMBER IN THE
001766  104004                        MULF                      ;*999/4095
001770  016767  177046  177030        MOV     F.C1,FTEMP
001776  104001                        ADDF                      ;+.5
002000  016767  177044  177020        MOV     F.C2,FTEMP
002006  104011                        FIX                       ;ABS()
002010  016767  177012  177010        MOV     FTEMP,FTEMP
002016  102275                        BVC     CP.SWI            ;GO IF OK
002020  000167  176152        CP.00:  JMP     KEY.0             ;ERROR
002024  016767  176776  000374 PATCH4: MOV    FTEMP,PTEMP
002032  104013                        FLT
002034  016767  000366  176764        MOV     PTEMP,FTEMP
002042  000207                        RTS     PC

```

```
002044                            C.PNCH:                               ;PUNCH CONTROL
002044  012700  002124'                   MOV     #PCHLST,R0            ;GET PROTOTYPES
002050  004767  175760                    JSR     PC.SRCH               ;FIND OUT WHAT TO DO
002054  000173  002114'                   JMP     @PJADR(R3)            ;JUMP TO ROUTINE
002060  005067  000000G           C.POFF: CLR     PCHFLG                ;PUNCH OFF
002064  000207                            RTS     PC
002066  012767  177777  000000G   C.PAUX: MOV     #-1,AUXFLG            ;FLAG ON FOR AUX DATA
002074  012767  177777  000000G   C.PON:  MOV     #-1,PCHFLG            ;PUNCH ON
002102  000207                            RTS     PC
002104  005067  000000G           C.NPAX: CLR     AUXFLG                ;FLAG OFF
002110  000207                            RTS     PC
002112  002074'                           C.PON
002114  002060'                   PJADR:  C.POFF
002116  002074'                           C.PON
002120  002066'                           C.PAUX
002122  002104'                           C.NPAX

002124                            PCHLST:
002124     003                            .BYTE   3
002125     117     106     106            .ASCII  /OFF/
002130     002                            .BYTE   2
002131     117     116                    .ASCII  /ON/
002133     003                            .BYTE   3
002134     101     125     130            .ASCII  /AUX/
002137     004                            .BYTE   4
002140     116     101     125            .ASCII  /NAUX/
002143     130
002144     000                            .BYTE   0
                                          .EVEN
```

```
002146                               C.DEPS:                          ;DEPOSIT
002146  005767  000000G                       TST     RISFLG          ;RISE PHASE?
002152  001402                                BEQ     .+6             ;NO
002154  000167  176016               CD.00:   JMP     KEY.Q           ;ERROR
002160  005767  000000G                       TST     SOKFLG          ;SOAK PHASE?
002164  001773                                BEQ     CD.00           ;ERROR IF NOT
002166  005067  000000G                       CLR     SOKFLG          ;TURN OFF SOAK
002172  012767  177777  000000G               MOV     #-1.DEPFLG      ;TURN ON DEPOSIT
002200  016767  000000G 000000G               MOV     S.DA.TEMP
002206  000207                                RTS     PC
```

```
002210  000003                  PROMPT: PBE-PBS
002212  000000                          0
002214  000003                          PBE-PBS
002216     015    012    072    PBS:    .BYTE   CR,LF,':
002221                          PBE:    .EVEN
002222  000003                  QUERY:  QBE-QBS
002224  000000                          0
002226  000003                          QBE-QBS
002230     077    015    012    QBS:    .BYTE '?,CR,LF
002233                          QBE:    .EVEN
002234  000120                  KBUFF:  KBE-KBIN
002236  000000                          0
002240  000000                  KBCT:   0
002242  002362'                 KBIN:   .=.+80.
002362                          KBE:    .EVEN
002362  000011                  IBUF:   IBE-IBS
002364  000000                          0
002366  000011                          IBE-IBS
002370  002377'                 IBUFS:IBS: .=.+7
002377     015    012                   .BYTE   CR,LF
002401                          IBE:    .EVEN
002402  000015                  FBUF:   FBE-FBS
002404  000000                          0
002406  000015                          FBE-FBS
002410  002423'                 FBUFS:FBS: .=.+11.
002423     015    012                   .BYTE   CR,LF
002425                          FBE:    .EVEN
002426  000000                  PTEMP:  .WORD 0

        000001'                         .END
```

CKI

Transfer Control to Proper Routine on Clock Interrupt

```
                        ;
                        ; PDP-11 CLOCK INTERRUPT HANDLER
                        ;
                        ; REV: 7/23/73
                        ;
                        ; CONTENTS:
                        ;       1. CKI
                        ;
                        ; THIS MODULE SERVICES THE 1 HERTZ CLOCK INTERRUPT AND
                        ; INITIATES THE CONTROLLER PROCESSES AT THE TIME OF
                        ; THE INTERRUPT.
                        ;
                                .TITLE  CKI
                                .GLOBL  CKI,TSEC,SEC,MIN,HR

                                .GLOBL  CTLMDX
                                .GLOBL  RISFLG
                                .GLOBL  SOKFLG
                                .GLOBL  DEPFLG

                        ; REGISTER ASSIGNMENTS

        000000          R0      =       %0
        000001          R1      =       %1
        000002          R2      =       %2
        000003          R3      =       %3
        000004          R4      =       %4
        000005          R5      =       %5
        000006          SP      =       %6
        000007          PC      =       %7

        177776          PS      =       177776

        000000          PRIO0   =       0
        000040          PRIO1   =       40
        000100          PRIO2   =       100
```

```
        000140          PRIO3   =       140
        000200          PRIO4   =       200
        000240          PRIO5   =       240
        000300          PRIO6   =       300
        000340          PRIO7   =       340

        177520          CKS     =       177520
        000000          DEV0    =       0

        104402          RISE    =       TRAP+2
        104403          SOAK    =       TRAP+3
        104404          DEPOS   =       TRAP+4

        000000                  .ASECT

        000660          .       =       660
000660  000010'         CKVEC:  CKI
000662  000240                  PRIO5
```

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```
        000000'                                 .CSECT
000000  000000                          TSEC:   .WORD   0
000002  000000                          SEC:    .WORD   0
000004  000000                          MIN:    .WORD   0
000006  000000                          HR:     .WORD   0

000010  042737  000100  177520          CKI:    BIC     #100,@#CKS      ;TURN CLOCK INT OFF
000016  005267  177756                          INC     TSEC            ;TOTAL SECONDS
000022  005267  177754                          INC     SEC             ;KEEP TIME
000026  026727  177750  000074                  CMP     SEC,#60.
000034  002422                                  BLT     CK.01
000036  005067  177740                          CLR     SEC
000042  005267  177736                          INC     MIN
000046  026727  177732  000074                  CMP     MIN,#60.
000054  002412                                  BLT     CK.01
000056  005067  177722                          CLR     MIN
000062  005267  177720                          INC     HR
000066  026727  177714  000030                  CMP     HR,#24.
000074  002402                                  BLT     CK.01
000076  005067  177704                          CLR     HR
000102                                  CK.01:
000102  005767  000000G                         TST     RISFLG          ;RISE ACTIVE?
000106  001401                                  BEQ     CK.02           ;NO
000110  104402                                  RISE                    ;YES - TRAP
000112  005767  000000G                 CK.02:  TST     SOKFLG          ;SOAK ACTIVE?
000116  001401                                  BEQ     CK.03           ;NO
000120  104403                                  SOAK                    ;YES - TRAP
000122  005767  000000G                 CK.03:  TST     DEPFLG          ;DEPOSITION ACTIVE?
000126  001401                                  BEQ     CK.04           ;NO
000130  104404                                  DEPOS                   ;YES - TRAP
000132                                  CK.04:
000132  012737  000204' 000660                  MOV     #CK.INT,@#CKVEC ;SET UP DUMMY INT
000140  004567  000000G                         JSR     R5,CTLMDX       ;SET UP CLOCK
000144  000000                                  DEV0
000146  052737  000100  177520                  BIS     #100,@#CKS      ;TURN ON CLOCK
000154  042737  000040  177776                  BIC     #PRIO1,@#PS     ;LOWER PRIORITY TO 4
```

```
000162  000240                           NOP                        ;LET INT THRU
000164  000240                           NOP
000166  052737  000240  177776           BIS      #PRIO5,@#PS       ;LOCK OUT IF NO INT
000174  012737  000010' 000660  CK.05:   MOV      #CKI,@#CKVEC      ;RESTORE VECTOR
000202  000002                           RTI
000204  022626                  CK.INT:  CMP      (SP)+,(SP)+       ;POP INT TRASH
000206  000772                           BR       CK.05             ;CLEAN UP

        000001'                          .END
```

TRPHND

Services Software Trap Instructions

```
                                    ;
                                    ; PDP-11 TRAP HANDLER
                                    ;
                                    ; REV: 8/1/73
                                    ;
                                    ; CONTENTS:
                                    ;       1. TRPHND
                                    ;       2. S.IOW
                                    ;
                                    ; THIS MODULE SERVICES THE "TRAP" INSTRUCTION
                                    ; AND THE "IOWAIT" TRAP CALL.
                                    ;
                                            .TITLE  TRPHND
                                            .GLOBL  TRPHND

        000000                              .ASECT
        000034                      .       =       34              ;TRAP VECTOR
000034  000000'                             TRPHND
000036  000340                              340                     ;RPIORITY 7

        000000'                             .CSECT

        000006                      SP      =       %6
        000007                      PC      =       %7
        177776                      PS      =       177776

                                            .GLOBL  S.IOW           ;IOWAIT
                                            .GLOBL  S.KEY           ;KEYIN
                                            .GLOBL  S.RISE          ;RISE
                                            .GLOBL  S.SOAK          ;SOAK
                                            .GLOBL  S.DEP           ;DEPOS

000000  016646  000002              TRPHND: MOV     2(SP),-(SP)     ;RESTORE USER PRIORITY
000004  042716  177437                      BIC     #177437,(SP)    ;CLEAR T BIT, ETC.
000010  052637  177776                      BIS     (SP)+,@#PS
000014  011646                              MOV     (SP),-(SP)      ;ADDR+2 OF TRAP INSTR
```

```
000016  162716  000002                 SUB     #2,(SP)         ;↑ TRAP INSTR
000022  013646                         MOV     @(SP)+,-(SP)    ;REPLACE W/TRAP INSTR
000024  042716  177400                 BIC     #177400,(SP)    ;LEAVE ONLY TRAP #
000030  006316                         ASL     (SP)            ;*2 FOR BYTES TO WORDS
000032  062716  000042'                ADD     #TRPTBL,(SP)    ;NOW POINTS TO ROUTINE
000036  013646                         MOV     @(SP)+,-(SP)    ; ADDR.: NOW TO ITSELF
000040  012607                         MOV     (SP)+,PC        ;GO..RETURN WITH RTI

000042  000054'               TRPTBL:  S.IOW   ;IOWAIT 000
000044  000000G                        S.KEY   ;KEYIN  001
000046  000000G                        S.RISE  ;RISE   002
000050  000000G                        S.SOAK  ;SOAK   003
000052  000000G                        S.DEP   ;DEPOS  004
```

```
                                      ;
                                      ; IOWAIT SERVICE ROUTINE
                                      ;

         000340                       PRIO7   =       340
         000004                       WAITR   =       IOT
         000004                       WAITC   =       4

000054   117667  000000  000017  S.IOW:   MOVB    @(SP),IOW.00     ;GET THE SLOT #
000062   062716  000002                   ADD     #2,(SP)          ;MOVE USER PC PAST IT
000066   052737  000340  177776  IOW.01:  BIS     #PRIO7,@#PS      ;LOCK OUT OTHERS
000074   000004                           WAITR                    ;CHECK WITH IOX
000076   000104'                          IOW.02
000100      004                           .BYTE   WAITC
000101      000                  IOW.00:  .BYTE   0                ;SLOT # GOES HERE
000102   000002                           RTI                      ;UNBUSY..RETURN
000104   042737  000340  177776  IOW.02:  BIC     #PRIO7,@#PS      ;LOWER PRIORITY
000112   000001                           WAIT                     ;WAIT FOR INTERRUPT
000114   000764                           BR      IOW.01           ;THEN ASK AGAIN

         000001'                          .END
```

RISE

Calculates Rise Increment

Steps D/A Each Second

Passes Control to Soak Routine

```
                ;
                ; RISE ROUTINE
                ;
                ;  REV:        4/13/74
                ;
                ; CONTENTS:
                ;          1. S.RISE
                ;
                ; THIS MODULE CONTROLS THE D/A CONVERTER OUTPUT
                ; DURING THE RISE PHASE OF DEPOSITION CONTROL.
                ;
                ; VARIABLES:
                ;
                ; R.FIN (SWI) FINAL SETPOINT. D/A CONVERTER
                ; R.STRT(SWI) INITIAL SETPOINT. D/A CONVERTER
                ; R.TIME(SWI) NUMBER OF SECONDS OF RISE TIME
                ; R.DA  (SWI) CURRENT D/A CONVERTER SETTING
                ; R.SEC (SWI) CUMULATIVE RISE TIME. SECONDS
                ; RISFLG(SWI) FLAG: 0=RISE PHASE OFF. -1=RISE PHASE ON
                ;
                        .TITLE  RISE
                        .GLOBL  MCOUNT.STORAT
                        .GLOBL  C1.XVEC         ;FOR CLEARING VARIABLES
                        .GLOBL  NCOUNT
                        .GLOBL  S.RISE.R.FIN.R.STRT.R.TIME.R.DA.RISFLG
                        .GLOBL  R.SEC

                        .GLOBL  CTLMDX.SOKFLG

        000000  DEV0    =       0
        177522  DACTL   =       177522
        000001  TTY     =       1
        000015  CR      =       015
        000012  LF      =       012
        104400  IOWAIT  =       TRAP

```

```
                        ; REGISTER ASSIGNMENTS

        000000          R0      =       %0
        000001          R1      =       %1
        000002          R2      =       %2
        000003          R3      =       %3
        000004          R4      =       %4
        000005          R5      =       %5
        000006          SP      =       %6
        000007          PC      =       %7

                        ; FPP-11 EMT CALLS

        104015          ITOA    =       EMT+15
        104033          MUL     =       EMT+33
        104034          DIV     =       EMT+34

                        ; IOX COMMAND CODES

        000012          WRIC    =       12

                        ; IOX CALLS

        000004          WRITE   =       IOT
```

```
          000000'                              .CSECT
   000000  000000                       R.FIN:   .WORD   0
   000002  000000                       R.STRT:  .WORD   0
   000004  000000                       R.TIME:  .WORD   0
   000006  000000                       R.DA:    .WORD   0
   000010  000000                       R.SEC:   .WORD   0
   000012  000000  000000               R.INC:   .WORD   0,0
   000016  000000                       RISFLG:  .WORD   0
   000020  016767  177754  177764       S.RISE:  MOV     R.FIN,R.INC      ;COMPUTE THE RISE INCR.
   000026  010146                                MOV     R1,-(SP)
   000030  010046                                MOV     R0,-(SP)
   000032  012700  000000G                       MOV     #C1,R0
   000036  012701  000000G                       MOV     #XVEC,R1
   000042  005020                       CLEAR:   CLR     (R0)+
   000044  020001                                CMP     R0,R1
   000046  001375                                BNE     CLEAR
   000050  012700  000000G                       MOV     #STORAT,R0
   000054  010001                                MOV     R0,R1
   000056  062701  000132                        ADD     #90.,R1
   000062  005020                       CLEAR2:  CLR     (R0)+
   000064  020001                                CMP     R0,R1
   000066  001375                                BNE     CLEAR2
   000070  005067  000000G                       CLR     NCOUNT
   000074  005067  000000G                       CLR     MCOUNT
   000100  012600                                MOV     (SP)+,R0
   000102  012601                                MOV     (SP)+,R1
   000104  166767  177672  177700                SUB     R.STRT,R.INC
   000112  003463                                BLE     RI.99            ;ERROR IF R.FIN<=R.STRT
   000114  005067  177674                        CLR     R.INC+2          ;DWI REQ'D FOR DIV
   000120  104034                                DIV
   000122  016767  177656  177662                MOV     R.TIME,R.INC     ;(R.FIN-R.STRT)/R.TIME
   000130  102454                                BVS     RI.99            ;IF DIVISOR TOO SMALL
   000132  005767  177654                        TST     R.INC            ;SEE IF OK
   000136  003003                                BGT     RI.01            ;>0, OK
```

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```
000140  012767  000001  177644            MOV     #1,R.INC          ;IF TOO SMALL, MAKE 1
000146  005767  177634          RI.01:    TST     R.DA              ;IS THIS START OF RISE?
000152  001004                            BNE     RI.04             ;NO
000154  016767  177622  177624            MOV     R.STRT,R.DA       ;YES, SET D/A UP
000162  000412                            BR      RI.02
000164  066767  177622  177614  RI.04:    ADD     R.INC,R.DA        ;STEP D/A ONWARD
000172  026767  177610  177600            CMP     R.DA,R.FIN        ;ARE WE AT END?
000200  101403                            BLOS    RI.02             ;NO
000202  016767  177572  177576            MOV     R.FIN,R.DA        ;YES, SET TO FINAL
000210  005267  177574          RI.02:    INC     R.SEC             ;COUNT TIME
000214  026767  177570  177562            CMP     R.SEC,R.TIME      ;OUT OF TIME?
000222  101410                            BLOS    RI.03             ;NO
000224  005067  177560                    CLR     R.SEC             ;YES
000230  005067  177562                    CLR     RISFLG
000234  012767  177777  000000G           MOV     #-1,SOKFLG
000242  000002                            RTI
000244  004567  000000G         RI.03:    JSR     R5,CTLMDX
000250  000000                            DEV0                      ;SET UP D/A
000252  016737  177530  177522            MOV     R.DA,@#DACTL      ;REFRESH SETTING
000260  000002                            RTI
000262  005067  177520          RI.99:    CLR     R.DA              ;ON ERROR, RESET ALL
000266  005067  177516                    CLR     R.SEC
000272  005067  177520                    CLR     RISFLG
000276  004567  000000G                   JSR     R5,CTLMDX
000302  000000                            DEV0
000304  005037  177522                    CLR     @#DACTL ;TURN D/A OFF
000310  104015                            ITOA                      ;PRINT OUT THE ERROR
000312  016767  177462  000132            MOV     R.FIN,RFOUT
000320  104015                            ITOA
000322  016767  177454  000100            MOV     R.STRT,RSOUT
000330  104015                            ITOA
000332  016767  177446  000133            MOV     R.TIME,RTOUT
000340  104400                            IOWAIT                    ;WAIT ON TTY
000342  000001                            TTY
000344  000004                            WRITE                     ;START I/O
000346  000354'                           R.EBUF
```

```
000350     012     001                      .BYTE   WRIC,TTY
000352  000002                              RTI

000354  000122                      R.EBUF: RBE-RBS
000356  000000                              0
000360  000122                              RBE-RBS
000362     015     012              RBS:    .BYTE   CR,LF
000364     111     116     126              .ASCII  /INVALID RISE PARAMETERS:/
000367     101     114     111
000372     104     040     122
000375     111     123     105
000400     040     120     101
000403     122     101     115
000406     105     124     105
000411     122     123     072
000414     015     012                      .BYTE   CR,LF
000416     123     124     101              .ASCII  @START D/A:@
000421     122     124     040
000424     104     057     101
000427     072
000430  000437'                     RSOUT:  .=.+7
000437     106     111     116              .ASCII  @FINISH D/A:@
000442     111     123     110
000445     040     104     057
000450     101     072
000452  000461'                     RFOUT:  .=.+7
000461     122     111     123              .ASCII  /RISE TIME:/
000464     105     040     124
000467     111     115     105
000472     072
000473  000502'                     RTOUT:  .=.+7
000502     015     012                      .BYTE   CR,LF
000504                              RBE:    .EVEN
000504  000000                      STORER: .WORD   0
        000001'                             .END
```

SOAK

Maintains D/A at Final Rise Value

Counts Seconds of Execution

Passes Control to Deposition Routine

```
                        ;
                        ; SOAK ROUTINE
                        ;
                        ; REV: 8/3/73
                        ;
                        ; CONTENTS:
                        ;       1. S.SOAK
                        ;
                        ; THIS MODULE CONTROLS THE D/A CONVERTER OUTPUT
                        ; DURING THE SOAK PHASE OF DEPOSITION CONTROL.
                        ;
                        ; VARIABLES:
                        ;
                        ; S.SEC (SWI) ELAPSED SOAK TIME, SECONDS
                        ; S.TIME(SWI) SOAK TIME SETPOINT, SECONDS
                        ; S.DA  (SWI) SOAK PHASE D/A CONVERTER SETTING
                        ; SOKFLG(SWI) FLAG: 0=SOAK OFF, -1=SOAK ON
                        ;
                                .TITLE  SOAK
                                .GLOBL  TEMP,D.AMIN
                                .GLOBL  S.SOAK,S.SEC,S.TIME,SOKFLG,S.DA

                                .GLOBL  CTLMDX,DEPFLG,R.DA

        000000          DEV0    =       0
        177522          DACTL   =       177522

                        ; REGISTER ASSIGNMENTS

        000000          R0      =       %0
        000001          R1      =       %1
        000002          R2      =       %2
        000003          R3      =       %3
        000004          R4      =       %4
        000005          R5      =       %5
        000006          SP      =       %6
```

```
        000007                  PC      =       %7

        177776                  PS      =       177776
```

```
        000000'                          .CSECT

000000  000000                  S.SEC:   .WORD   0
000002  000004'                 S.TIME:  .=.+2
000004  000000                  S.DA:    .WORD   0
000006  000000                  SOKFLG:  .WORD   0

000010  005767  177764          S.SOAK:  TST     S.SEC           ;FIRST TIME THRU?
000014  001003                           BNE     S.CNT           ;NO
000016  016767  000000G 177760           MOV     R.DA,S.DA       ;PICK UP D/A SETTING
000024  005267  177750          S.CNT:   INC     S.SEC           ;COUNT TIME
000030  026767  177744  177744           CMP     S.SEC,S.TIME    ;ARE WE THROUGH?
000036  003007                           BGT     S.FIN           ;YES
000040  004567  000000G                  JSR     R5,CTLMDX       ;NO
000044  000000                           DEV0
000046  016737  177732  177522           MOV     S.DA,@#DACTL    ;SET D/A
000054  000002                           RTI
000056  005067  177724          S.FIN:   CLR     SOKFLG
000062  005067  177712                   CLR     S.SEC
000066  012767  177777  000000G          MOV     #-1,DEPFLG
000074  016767  177704  000000G          MOV     S.DA,TEMP       ;STORE THE SOAK VALUE
000102  000002                           RTI
        000001'                          .END
```

DEPOS

Obtains Freq. Value

Calculates Rate Value

Calls APPASX Routine

Compares D/A Value for Max/Min

Assigns Multiplexer Channels

Sets D/A Values

Commands Punch Routine

```
;
; DEPOSITION ROUTINE
;
;  REV: 6/19/74
;
; CONTENTS:
;       1. S.DEP
;       2. DASET
;
; THIS MODULE CONTROLS THE D/A CONVERTER OUTPUT DURING
; THE ACTUAL DEPOSITION PHASE. IT RELIES UPON MODULE
; APASSX TO COMPUTE THE CONTROL VARIABLE. ENTRY DASET
; IS CALLED FROM APASSX TO SET UP THE D/A CONVERTER.
;
; VARIABLES:
;
; D.TIME(SWI) DEPOSITION TIME LIMIT, SECONDS
; D.SEC (SWI) CURRENT ELAPSED DEPOSITION TIME, SECONDS
; D.M   (FPN) SCALE MULTIPLIER, USED IN CONVERSION OF
;                 IDVM READING IN VOLTS TO FREQUENCY
; D.O   (FPN) SCALE OFFSET, VOLTAGE TO FREQUENCY
; CREF  (FPN) DESIRED RATE, HERTZ/SECOND
; D.FLIM(FPN) LIMIT OF DEPOSITION FREQUENCY
; D.DLO (SWI) LOWER LIMIT, D/A SETTING
; D.DFLO(FPN) LOWER LIMIT, D/A SETTING
; D.DHI (SWI) UPPER LIMIT, D/A SETTING
; D.DFHI(FPN) UPPER LIMIT, D/A SETTING
; DEPFLG(SWI) FLAG: 0=DEPOSITION PHASE OFF, -1=ON
; DTHFLG(SWI) FLAG: 0=DEPOSITION NOT FINISHED, -1=FIN.
; PCHFLG(SWI) FLAG: 0=NO DATA PUNCHED, -1=PUNCH DATA
; AUXFLG(SWI) FLAG: 0=NO PUNCH ALPHA-B2, -1=PUNCH
; DATMP (SWI) DEPOSITION POWER, CURRENT
; RATE  (FPN) CURRENT RATE
; FLAST (FPN) CURRENT FREQUENCY
;
        .TITLE  DEPOS
```

```
                        .GLOBL  STORER
                        .GLOBL  AVERAT
                        .GLOBL  COUNT,NUMBER
                        .GLOBL  MCOUNT,MNUM
                        .GLOBL  ADD,D.DSTG
                        .GLOBL XVEC
                        .GLOBL  S.DEP,DASET
                        .GLOBL  D.TIME,D.SEC,D.M,D.O,D.FLIM
                        .GLOBL  D.DLO,D.DFLO,D.DHI,D.DFHI
                        .GLOBL  CREF,ALPHA,BETA
                        .GLOBL  A1,A2,B1,B2
                        .GLOBL  C1,C2,C3,M1,M2,M3
                        .GLOBL  E1,E2,E3
                        .GLOBL  ARR1,NEQ,DEPFLG,DTHFLG,DATMP,RATE
                        .GLOBL  PCHFLG,AUXFLG,FLAST

                        .GLOBL  CTLMDX,SIMUL,APASS1,APASS2,APASS3
                        .GLOBL  ENCODE,BCDTOF
                        .GLOBL  METER,DVMHI,DVMLO,DVM1,DVM2

                ; REGISTER ASSIGNMENTS

        000000  R0      =       %0
        000001  R1      =       %1
        000002  R2      =       %2
        000003  R3      =       %3
        000004  R4      =       %4
        000005  R5      =       %5
        000006  SP      =       %6
        000007  PC      =       %7

        177776  PS      =       177776

                ; FPP-11 EMT CALLS

        104001  ADDF    =       EMT+1
```

```
        104002          SUBF    =       EMT+2
        104003          NEGF    =       EMT+3
        104004          MULF    =       EMT+4
        104005          DIVF    =       EMT+5
        104007          MOVF    =       EMT+7
        104010          CMPF    =       EMT+10
        104011          FIX     =       EMT+11
        104013          FLT     =       EMT+13
        104033          MUL     =       EMT+33
        104034          DIV     =       EMT+34

        000200          FAM     =       200
        000100          PM      =       100

                        ; IOX COMMAND CODES

        000005          SEEC    =       5
        000012          WRIC    =       12

                        ; IOX CALLS

        000004          SEEK    =       IOT
        000004          WRITE   =       IOT

        000001          TTY     =       1
        000003          HSP     =       3
        000015          CR      =       015
        000012          LF      =       012
        104400          IOWAIT  =       TRAP
        177522          DACTL   =       177522
        000000          DEV0    =       0
```

```
        000000'                              .CSECT
000000  000000                      DEPFLG:  .WORD   0
000002  000000                      DTHFLG:  .WORD   0
000004  000000                      PCHFLG:  .WORD   0
000006  000000                      AUXFLG:  .WORD   0
000010  000012'                     D.TIME:  .=.+2
000012  000014'                     D.SEC:   .=.+2
000014  103453   072232   100013    D.M:     .WORD   103453,072232,100013     ;1865.658
000022  074550   123136   100006    D.O:     .WORD   074550,123136,100006     ;-44.81548
000030  000036'                     CREF:    .=.+6
000036  000040'                     D.DLO:   .=.+2
000040  000046'                     D.DFLO:  .=.+6
000046  000050'                     D.DHI:   .=.+2
000050  000056'                     D.DFHI:  .=.+6
000056  000064'                     D.FLIM:  .=.+6
000064  000072'                     ALPHA:   .=.+6    ;DO      1
000072  000100'                     BETA:    .=.+6    ;NOT     2
000100  000106'                     A1:      .=.+6    ;DISTURB3
000106  000114'                     A2:      .=.+6    ;THE     4
000114  000122'                     B1:      .=.+6    ;ORDER   5
000122  000130'                     B2:      .=.+6    ;HERE    6
000130  000136'                     C1:      .=.+6
000136  000144'                     C2:      .=.+6
000144  000152'                     C3:      .=.+6
000152  000160'                     M1:      .=.+6
000160  000166'                     M2:      .=.+6
000166  000174'                     M3:      .=.+6
000174  000202'                     E1:      .=.+6
000202  000210'                     E2:      .=.+6
000210  000216'                     E3:      .=.+6
000216  000246'                     XVEC:    .=.+24.
000246  000436'                     ARR1:    .=.+120.
000436  000440'                     NEO:     .=.+2
000440  000462'                     D.RSTG:  .=.+18.
000462  000470'                     D.DSTG:  .=.+6.
```

ORIGINAL PAGE IS
OF POOR QUALITY

```
000470                          S.DEP:                               ;DEPOS
000470  010546                          MOV    R5,-(SP)
000472  010446                          MOV    R4,-(SP)
000474  010346                          MOV    R3,-(SP)
000476  010246                          MOV    R2,-(SP)
000500  010146                          MOV    R1,-(SP)
000502  010046                          MOV    R0,-(SP)
000504  005767  177302                  TST    D.SEC                 ;1ST TIME THRU?
000510  001540                          BEQ    DFIRST                ;YES
000512  026767  177274  177270          CMP    D.SEC,D.TIME          ;TIME LIMIT EXCEEDED?
000520  003402                          BLE    .+6
000522  000167  000370                  JMP    DTHRU
000526  004767  001004                  JSR    PC,RMTR               ;NO--MEASURE FREQ.
000532  104007                          MOVF                         ;GET THE RATE
000534  011067  001206                  MOV    (R0),RATE
000540  104002                          SUBF
000542  011167  001200                  MOV    (R1),RATE
000546  104007                          MOVF                         ;REPLACE OLD FREQ W/NEW
000550  011011                          MOV    (R0),(R1)
000552  005767  177302                  TST    D.FLIM+2              ;IS A FREQ LIM. SET?
000556  001404                          BEQ    DE.01                 ;NO
000560  104010                          CMPF                         ;YES-SEE IF FREQ>=LIMIT
000562  011167  177270                  MOV    (R1),D.FLIM           ;FREQ:SETPOINT
000566  002153                          BGE    DTHRU                 ;FINISHED
000570  012700  001742'         DE.01:  MOV    #D.SS,R0              ;*
000574  016720  177212                  MOV    D.SEC,(R0)+           ;TEMP STORE
000600  005010                          CLR    (R0)                  ;DWI
000602  005340                          DEC    -(R0)                 ;0-ORIGIN
000604  104034                          DIV
000606  016710  001176                  MOV    D.3,(R0)              ;D.SEC/3
000612  005720                          TST    (R0)+                 ;BACK UP TO 2ND WORD
000614  005710                          TST    (R0)                  ;1ST PASS?
000616  001002                          BNE    DE.03                 ;NO
000620  004767  000534                  JSR    PC,PCHDTA             ;YES-DO PUNCHING NOW
000624  011001                  DE.03:  MOV    (R0),R1               ;GET REMAINDER 0-2
000626  006301                          ASL    R1                    ;BYTES TO WORDS
```

```
000630  004767  000000G                 JSR     PC,AVERAT
000634  104007                          MOVF                    ;MOVE RATE TO PROPER C
000636  016771  001104  001774'         MOV     RATE,@CTBL(R1)
000644  104007                          MOVF                    ;MOVE TO SAFE PLACE(TOO
000646  016771  001074  001766'         MOV     RATE,@RTBL(R1)
000654  010600                          MOV     SP,R0           ;FORM R0 STACK
000656  162706  000074                  SUB     #60.,SP         ; FROM SP STACK
000662  005267  001066                  INC     MCOUNT
000666  026767  001062  001062          CMP     MCOUNT,NNUM
000674  001033                          BNE     DE.02
000676  005067  001052                  CLR     MCOUNT
000702  104003                          NEGF
000704  016767  177204  177166          MOV     B1,A1
000712  104010                          CMPF
000714  016767  177160  177172          MOV     A1,B1
000722  001001                          BNE     CHANG3
000724  000410                          BR      PAT1
000726  104003                  CHANG3: NEGF
000730  016767  177160  177142          MOV     B1,A1
000736  104007                          MOVF
000740  016767  177134  177146          MOV     A1,B1
000746  004771  002002'         PAT1:   JSR     PC,@PTBL(R1)    ;DO APASSX
000752  026727  000766  000002          CMP     D.SS+2,#2       ;PASS 3?
000760  001001                          BNE     DE.02           ;NO
000762  000400                          BR      DE.02
000764  005267  177022          DE.02:  INC     D.SEC           ;COUNT TIME
000770  062706  000074                  ADD     #60.,SP         ;THROW AWAY STACK AT R0
000774  012600                  RTN:    MOV     (SP)+,R0
000776  012601                          MOV     (SP)+,R1
001000  012602                          MOV     (SP)+,R2
001002  012603                          MOV     (SP)+,R3
001004  012604                          MOV     (SP)+,R4
001006  012605                          MOV     (SP)+,R5
001010  000002                          RTI
001012  004767  000520          DFIRST: JSR     PC,RMTR         ;GET INITIAL READING
001016  104007                          MOVF
```

```
001020  011011                          MOV     (R0),(R1)       ;MOVE METER TO FLAST
001022  005267  176764                  INC     D.SEC
001026  005067  000732                  CLR     BLKCT
001032  005767  176746                  TST     PCHFLG          ;PUNCHING DATA?
001036  001756                          BEQ     RTN             ;NO
001040  000004                          SEEK                    ;YES, START IT UP
001042  000000                          0
001044     005     003                  .BYTE   SEEC,HSP
001046  104400                          IOWAIT
001050  000003                          HSP
001052  000004                          WRITE                   ;PUNCH NULLS
001054  001610'                         NULBUF
001056     012     003                  .BYTE   WRIC,HSP
001060  012701  000440'                 MOV     #D.RSTG,R1
001064  012702  000011                  MOV     #9.,R2          ;3 FPN * 3 WORDS PER
001070  005021                  D.I01:  CLR     (R1)+           ;CLEAR OLD RATES
001072  005302                          DEC     R2
001074  003375                          BGT     D.I01
001076  012701  000462'                 MOV     #D.DSTG,R1
001102  012702  000003                  MOV     #3,R2
001106  005021                  D.I02:  CLR     (R1)+           ;CLEAR OLD D/A
001110  005302                          DEC     R2
001112  003375                          BGT     D.I02
001114  000727                          BR      RTN
001116  004567  000000G         DTHRU:  JSR     R5,CTLMDX
001122  000000                          DEV0
001124  005037  177522                  CLR     @#DACTL         ;TURN OFF D/A
001130  005067  176644                  CLR     DEPFLG
001134  012767  177777  176640          MOV     #-1,DTHFLG      ;FLAG DEPOSITION AS THRU
001142  005767  176636                  TST     PCHFLG          ;PUNCH?
001146  001712                          BEQ     RTN             ;NO
001150  012700  001742'                 MOV     #D.SS,R0        ;↑
001154  016720  176632                  MOV     D.SEC,(R0)+     ;SECONDS OF DEPOSITION
001160  005010                          CLR     (R0)
001162  005340                          DEC     -(R0)
001164  104034                          DIV                     ;/3
```

```
001166  016710  002616          MOV     D.3,(R0)        ;ADJUST ↑ TO REMAINDER
001172  005720                  TST     (R0)+           ;PUNCH REST OF DATA
001174  004767  000160          JSR     PC,PCHDTA
001200  104400                  IOWAIT
001202  000003                  HSP
001204  005267  000554          INC     BLKCT           ;WRITE LAST BLOCK
001210  012701  001642'         MOV     #PBUFS+4,R1     ;↑
001214  016741  176572          MOV     D.SEC,-(R1)
001220  016741  000540          MOV     BLKCT,-(R1)
001224  012741  000004          MOV     #4,-(R1)        ;BYTE COUNT
001230  000004                  WRITE
001232  001630'                 PBUF
001234     012     003          .BYTE   WRIC,HSP
001236  000656                  BR      RTN

001240  010246          DASET:  MOV     R2,-(SP)
001242  010146                  MOV     R1,-(SP)
001244  012501                  MOV     (R5)+,R1
001246  012702  002022'         MOV     #DATMP,R2       ;↑
001252  104010                  CMPF
001254  011167  176560          MOV     (R1),D.DFLO
001260  003006                  BGT     DAS.01
001262  016712  176550          MOV     D.DLO,(R2)
001266  104007                  MOVF
001270  016711  176544          MOV     D.DFLO,(R1)
001274  000414                  BR      DAS.03
001276  104010          DAS.01: CMPF
001300  011167  176544          MOV     (R1),D.DFHI
001304  002405                  BLT     DAS.02
001306  016712  176534          MOV     D.DHI,(R2)
001312  104007                  MOVF
001314  016711  176530          MOV     D.DFHI,(R1)
001320  000402                  BR      DAS.03
001322  104011          DAS.02: FIX
001324  011112                  MOV     (R1),(R2)
001326  004567  000000G DAS.03: JSR     R5,CTLMDX
```

```
001332  000000                     DEV0
001334  004767  000000G            JSR     PC,ADD
001340  016701  000400             MOV     D.SS+2,R1          ;GET PASS #
001344  006301                     ASL     R1
001346  011261  000462'            MOV     (R2),D.DSTG(R1)
001352  012601                     MOV     (SP)+,R1
001354  012602                     MOV     (SP)+,R2
001356  000205                     RTS     R5

001360  005767  176420     PCHDTA: TST     PCHFLG             ;PUNCH ON?
001364  001463                     BEQ     P.FIN              ;NO
001366  011004                     MOV     (R0),R4            ;R4=#PASSES TO PUNCH
001370  001002                     BNE     .+6
001372  012704  000003             MOV     #3,R4              ;0==>ALL 3 PASSES
001376  005005                     CLR     R5                 ;BYTE COUNT
001400  104400                     IOWAIT
001402  000003                     HSP
001404  012701  001636'            MOV     #PBUFS,R1          ;START OF BUFFER
001410  005267  000350             INC     BLKCT
001414  116721  000344             MOVB    BLKCT,(R1)+        ;MOVE BLOCK #
001420  110421                     MOVB    R4,(R1)+           ;MORE #PASSES THIS BLOCK
001422  062705  000002             ADD     #2,R5              ;BYTE COUNT
001426  012702  000440'            MOV     #D.RSTG,R2         ;↑ RATE STORAGE
001432  010403                     MOV     R4,R3              ;COUNT
001434  104007             P.MOVR: MOVF                       ;MOVE A RATE
001436  012221                     MOV     (R2)+,(R1)+
001440  062705  000006             ADD     #6,R5
001444  005303                     DEC     R3
001446  003372                     BGT     P.MOVR
001450  012702  000462'            MOV     #D.DSTG,R2         ;↑ D/A STORAGE
001454  010403                     MOV     R4,R3
001456  012221             P.MOVD: MOV     (R2)+,(R1)+        ;MOVE A D/A
001460  062705  000002             ADD     #2,R5
001464  005303                     DEC     R3
001466  003373                     BGT     P.MOVD
001470  005767  176312             TST     AUXFLG             ;AUXILLARY DATA WANTED?
```

```
001474  001412                            BEQ     P.MFIN            ;NO
001476  012702  000064'                   MOV     #ALPHA,R2         ;↑ AUX. DATA
001502  012703  000006                    MOV     #6,R3             ;6 DATA
001506  062705  000044                    ADD     #36.,R5           ;ADJUST BYTE COUNT
001512  104007                   P.MOVX:  MOVF
001514  012221                            MOV     (R2)+,(R1)+
001516  005303                            DEC     R3
001520  003374                            BGT     P.MOVX
001522  010567  000106           P.MFIN:  MOV     R5,PBCT           ;EMPLACE BYTE COUNT
001526  000004                            WRITE
001530  001630'                           PBUF
001532     012     003                    .BYTE   WRIC,HSP
001534  000207                   P.FIN:   RTS     PC

001536  004767  000000G          RMTR:    JSR     PC,ENCODE         ;READ THE METER
001542  016767  000000G 000000G           MOV     DVMLO,DVM1        ;SET UP
001550  016767  000000G 000000G           MOV     DVMHI,DVM2        ;FOR BCDTOF
001556  004767  000000G                   JSR     PC,BCDTOF         ;CVRT TO FPN
001562  012700  000000G                   MOV     #METER,R0         ;↑
001566  012701  001734'                   MOV     #FLAST,R1         ;↑
001572  104004                            MULF
001574  016710  176214                    MOV     D.M,(R0)          ;METER*SCALE
001600  104001                            ADDF
001602  016710  176214                    MOV     D.O,(R0)          ;+OFFSET
001606  000207                            RTS     PC

001610  000012                   NULBUF:  NBE-NBS
001612  000003                            3
001614  000012                            NBE-NBS
001616  000000  000000  000000   NBS:     .WORD   0,0,0,0,0
001624  000000  000000
001630                           NBE:     .EVEN
001630  000076                   PBUF:    PBE-PBUFS
001632  000001                            1
001634  000000                   PBCT:    0
001636  001734'                  PBUFS:   .=.+62.
```

ORIGINAL PAGE IS
OF POOR QUALITY

```
001734                             PBE:     .EVEN

001734  001742'                    FLAST:   .=.+6
001742  001746'                    D.SS:    .=.+4
001746  001754'                    RATE:    .=.+6
001754  000000                     MCOUNT:  .WORD   0
001756  000000                     MNUM:    .WORD   0
001760  000000                     NUMBER:  .WORD   0
001762  000000                     COUNT:   .WORD   0
001764  000000                     BLKCT:   .WORD   0
001766  000440' 000446' 000454'    RTBL:    .WORD   D.RSTG,D.RSTG+6.,D.RSTG+12.
001774  000130' 000136' 000144'    CTBL:    .WORD   C1,C2,C3
002002  000000G 000000G 000000G    PTBL:    .WORD   APASS1,APASS2,APASS3
002010  000003                     D.3:     .WORD   3
002012  000006                     D.6:     .WORD   6
002014  000000  000000  000000     F.0:     .WORD   0,0,0
002022  000000                     DATMP:   .WORD   0
        000001'                             .END
```

APPASX

Calculates Rate Error from Rate Value

Calculates Controller Output

*Note: At the end of each pass a return from subroutine should be added.

```
                        ;
                        ; PDP-11 SELF-OPTIMIZING CONTROLLER
                        ;
                        ; REV:  6/19/74
                        ;
                        ; CONTENTS:
                        ;       1. APASS1
                        ;       2. APASS2
                        ;       3. APASS3
                        ;
                        ; THIS MODULE COMPUTES THE CONTROL VARIABLE, M,
                        ; GIVEN THE REFERENCE INPUT, CREF, AND THE SYSTEM
                        ; OUTPUT, C.  IT ALSO COMPUTES THE FILTERED VARIABLES,
                        ; CBAR AND MBAR, AS WELL AS THE PSEUDO-CORRELATION
                        ; FUNCTIONS, PXXXX.
                        ;
                        ; CALLING CONVENTION:
                        ;
                        ;       JSR     PC,APASS<X>     ;<X>=1,2, OR 3
                        ;
                                .TITLE  APASSX
        000000'                 .CSECT
                                .GLOBL  APASS1,APASS2,APASS3

                                .GLOBL  CREF
                                .GLOBL  ALPHA,BETA
                                .GLOBL  A1,A2,B1,B2
                                .GLOBL  C1,C2,C3
                                .GLOBL  E1,E2,E3
                                .GLOBL  M1,M2,M3
                                .GLOBL  DASET

                        ; REGISTER ASSIGNMENTS

        000000          R0      =       %0
        000001          R1      =       %1
```

```
000002          R2      =       %2
000003          R3      =       %3
000004          R4      =       %4
000005          R5      =       %5
000006          SP      =       %6
000007          PC      =       %7

177776          PS      =       177776

                ; FPP-11 EMT CALLS

104001          ADDF    =       EMT+1
104002          SUBF    =       EMT+2
104003          NEGF    =       EMT+3
104004          MULF    =       EMT+4
104005          DIVF    =       EMT+5
104006          NORM    =       EMT+6
104007          MOVF    =       EMT+7
104010          CMPF    =       EMT+10
104011          FIX     =       EMT+11
104012          FIXD    =       EMT+12
104013          FLT     =       EMT+13
104014          FLTD    =       EMT+14
104015          ITOA    =       EMT+15
104016          JTOA    =       EMT+16
104017          FTOA    =       EMT+17
104020          ETOA    =       EMT+20
104021          OTOA    =       EMT+21
104022          ATOI    =       EMT+22
104023          ATOF    =       EMT+23
104024          ATOO    =       EMT+24
104025          COS     =       EMT+25
104026          SIN     =       EMT+26
104027          ATAN    =       EMT+27
104030          LOG     =       EMT+30
104031          EXP     =       EMT+31
```

```
104032          SQRT    =       EMT+32
104033          MUL     =       EMT+33
104034          DIV     =       EMT+34

000200          FAM     =       200
000100          PM      =       100
```

```
                                 ;
                                 ; APASS1 -- PASS 1 OF CONTROL ALGORITHM
                                 ;
000000                           APASS1:                           ;JSR PC,APASS1

                                 ; E1=CREF-C1  COMPUTE ERROR

000000  104007                         MOVF
000002  016740  000000G                MOV    CREF,-(R0)
000006  104002                         SUBF
000010  016710  000000G                MOV    C1,(R0)
000014  104007                         MOVF
000016  011067  000000G                MOV    (R0),E1              ;LEAVE E1 ON STACK

                                 ;  M1=(E1-B1*E3+B1*E1)

000022  104007                         MOVF
000024  016740  000000G                MOV    B1,-(R0)
000030  104004                         MULF
000032  016710  000000G                MOV    E3,(R0)
000036  104101                         ADDF+PM
000040  104007                         MOVF
000042  016740  000000G                MOV    B2,-(R0)
000046  104004                         MULF
000050  016710  000030G                MOV    E1,(R0)
000054  104101                         ADDF+PM
000056  104007                         MOVF
000060  012067  000000G                MOV    (R0)+,M1             ;POP M1

                                 ; CALL DASET TO SET UP D/A CONVERTER

000064  004567  000000G                JSR    R5,DASET
000070  000000G                        M1

                                 ; END OF PASS 1 -- RETURN

```

```
000072  000207          RTS     PC
```

```
                                ;
                                ; APASS2 -- PASS 2 OF CONTROL ALGORITHM
                                ;
000074                          APASS2:                         ;JSR PC,APASS2

                                ; E2=CREF-C2

000074  104007                          MOVF
000076  016740  000000G                 MOV     CREF,-(R0)
000102  104002                          SUBF
000104  016710  000000G                 MOV     C2,(R0)
000110  104007                          MOVF
000112  011067  000000G                 MOV     (R0),E2         ;LEAVE E2 ON STACK

                                ;  M2=(E2-B1*E2+B1*E1)

000116  104007                          MOVF
000120  016740  000000G                 MOV     B1,-(R0)
000124  104004                          MULF
000126  016710  000000G                 MOV     E1,(R0)
000132  104101                          ADDF+PM
000134  104007                          MOVF
000136  016740  000000G                 MOV     B2,-(R0)
000142  104004                          MULF
000144  016710  000000G                 MOV     E2,(R0)
000150  104101                          ADDF+PM
000152  104007                          MOVF
000154  012067  000000G                 MOV     (R0)+,M2        ;POP M2

                                ; CALL DASET TO SET UP D/A CONVERTER

000160  004567  000000G                 JSR     R5,DASET
000164  000000G                         M2

                                ; END OF PASS 2 -- RETURN

```

```
37 000166  000207                    RTS     PC
```

```
                              ;
                              ; APASS3 -- PASS 3 OF CONTROL ALGORITHM
                              ;
000170                        APASS3:                            ;JSR PC,APASS3

                              ; E3=CREF-C3

000170  104007                        MOVF
000172  016740  000000G               MOV     CREF,-(R0)
000176  104002                        SUBF
000200  016710  000000G               MOV     C3,(R0)
000204  104007                        MOVF
000206  011067  000000G               MOV     (R0),E3            ;LEAVE E3 ON STACK

000212  104007                        MOVF
000214  016740  000000G               MOV     B1,-(R0)
000220  104004                        MULF
000222  016710  000000G               MOV     E2,(R0)
000226  104101                        ADDF+PM
000230  104007                        MOVF
000232  016740  000000G               MOV     B2,-(R0)
000236  104004                        MULF
000240  016710  000000G               MOV     E3,(R0)
000244  104101                        ADDF+PM
000246  104007                        MOVF
000250  012067  000000G               MOV     (R0)+,M3           ;POP M3

                              ; CALL DASET TO SET UP D/A CONVERTER

000254  004567  000000G               JSR     R5,DASET
000260  000000G                       M3

                              ; END OF PASS 3 -- RETURN

000262  000207                        RTS     PC

```

ADD

Stores D/A Values Between Samples

Sets Max/Min D/A Values

```
                                ;
                                ;  ADD ON VALUE OF CONTROLLER TO OBTAIN THE D/A
                                ;  SETTING
                                ;
                                ;
                                ;  REV:          4/13/74
                                ;
                                ;
                                       .TITLE  ADD
                                       .GLOBL  ADD

                                       .GLOBL  S.DA
                                       .GLOBL  D.AMIN
                                       .GLOBL  D.AMAX.TEMP.BEGIN.DASET
       000000'                         .CSECT
                                ;
                                ;
                                ;  REGISTER & ADDRESS ASSIGNMENT
       000007                          PC      =       %7
       000002                          R2      =       %2
       177522                          DACTL   =       177522
                                ;
                                ;
                                ;
                                ;
000000 016767  000000G 000076   ADD:   MOV     S.DA.D.AMAX
000006 062767  000100  000070          ADD     #100.D.AMAX
000014 016767  000000G 000066          MOV     S.DA.D.AMIN
000022 162767  000100  000060          SUB     #100.D.AMIN
000030 061267  000052           BEGIN: ADD     (R2).TEMP
000034 026767  000046  000042          CMP     TEMP.D.AMAX
000042 003404                          BLE     LOOP1
000044 016767  000034  000034          MOV     D.AMAX.TEMP
000052 000407                          BR      LOOP3
000054 026767  000026  000026   LOOP1: CMP     TEMP.D.AMIN
000060 002003                          BGE     LOOP3
```

```
000064  016767  000020  000014           MOV     D.AMIN,TEMP
000072  016712  000010          LOOP3:   MOV     TEMP,(R2)
000076  011237  177522                   MOV     (R2),@#DACTL
000102  000207                           RTS     PC
000104  000000                  D.AMAX:  .WORD 0
000106  000000                  TEMP:    .WORD 0
000110  000000                  D.AMIN:  .WORD   0
        000001'                                  .END
```

DACQ

Controls Multiplex Values for DMM

Commands Measurements

Conversion from BCD format to 3 Word Floating Point

```
;
; DATA ACQUISITION SYSTEM DRIVER
;
; REV: 7/25/73
;
; CONTENTS:
;       1. DAQEVL
;       2. DAQSUP
;       3. SENCDE
;       4. ENCODE
;       5. BCDTOF
;
; THIS MODULE IMPLEMENTS CONTROL OF THE HP 2402A IDVM
; AND THE HP 2911 CROSSBAR SCANNER SYSTEMS.  ENTRY
; DAQEVL DOES DATA CONVERSION FOR CHANNEL, FUNCTION, AND
; RANGE ENCODING.  ENTRY DAQSUP DOES THE ACTUAL SETUP OF
; THE DEVICES.  ENTRY SENCDE INITIATES A METER READING
; AFTER WAITING FOR THE CROSSBAR SCANNER TO COMPLETE
; CONNECTIONS.  ENTRY ENCODE INITIATES A METER READING.
; ENTRY BCDTOF CONVERTS THE BCD METER READING TO
; FLOATING POINT.
;
; CALLING CONVENTION:
;
;       JSR     PC,<X>  ;<X>:=DAQEVL,DAQSUP,SENCDE,
;                       ;ENCODE,BCDTOF
;
; VARIABLES:
;
; FUNC  (SWI) FUNCTION: 0=FREQUENCY, 1=RESISTANCE,
;       2=VOLTAGE
; RANGE (SWI) RANGE: 4=AUTORANGE, 5=.1V, 6=1V/1K,
;       7=10V/10K, 8=100V/.1MEG, 9=10MEG, OTHER=1KV/1MEG
; CHAN  (SWI) CHANNEL TO BE CONNECTED
; DACO1 (SWI) IDVM CONTROL BITS (OUTPUT OF DAQEVL)
; DACO2 (SWI) XBAR CONTROL BITS (OUTPUT OF DAQEVL)
```

```
                        ; DACQ3 (SWI) IDVM CONTROL BITS (INPUT TO DAQSUP)
                        ; DACQ4 (SWI) XBAR CONTROL BITS (INPUT TO DAQSUP)
                        ; DVMLO (SWI) LOW ORDER MEASUREMENT BITS
                        ; DVMHI (SWI) HIGH ORDER MEASUREMENT BITS
                        ; DVM1  (SWI) LOW ORDER MEASUREMENT BITS TO BCDTOF
                        ; DVM2  (SWI) HIGH ORDER MEASUREMENT BITS TO BCDTOF
                        ; METER (FPN) METER READING AFTER BCDTOF
                        ;
                                .TITLE  DACQ
        000000'                 .CSECT
                                .GLOBL  DAQEVL,DAQSUP,SENCDE,ENCODE,BCDTOF
                                .GLOBL  FUNC,RANGE,CHAN,DACQ1,DACQ2,DVMLO,DVMHI
                                .GLOBL  DACQ3,DACQ4,DVM1,DVM2
                                .GLOBL  METER

                                .GLOBL  CTLMDX

        000000          R0      =       %0
        000001          R1      =       %1
        000002          R2      =       %2
        000003          R3      =       %3
        000004          R4      =       %4
        000005          R5      =       %5
        000006          SP      =       %6
        000007          PC      =       %7

        177776          PS      =       177776

                        ; FPP-11 EMT CALLS

        104023          ATOF    =       EMT+23

        000200          FAM     =       200
        000100          PM      =       100

        177522          SCNCTL  =       177522  ;DEV2 OUT
```

```
        177524          DVHI    =       177524  ;DEV2 IN
        177522          DVMCTL  =       177522  ;DEV1 OUT
        177524          DVLO    =       177524  ;DEV1 IN
        177524          CHNID   =       177524  ;DEV0 IN

        000000          DEV0    =       0
        000001          DEV1    =       1
        000002          DEV2    =       2
```

```
000000  000000                  FUNC:   .WORD   0
000002  000000                  RANGE:  .WORD   0
000004  000000                  CHAN:   .WORD   0
000006  000000                  DACO1:  .WORD   0
000010  000000                  DACO2:  .WORD   0
000012  177777                  DACQ3:  .WORD   -1
000014  000003                  DACO4:  .WORD   3
000016  000000                  DVMHI:  .WORD   0
000020  000000                  DVMLO:  .WORD   0
000022  000000                  DVM1:   .WORD   0
000024  000000                  DVM2:   .WORD   0
000026  000000  000000  000000  METER:  .WORD   0,0,0


                                ; ENCODE FUNCTION, RANGE, & CHANNEL INFORMATION

                                ; (1) EVALUATE FUNCTION
000034                          DAQEVL:                          ;JSR PC,DAQEVL
000034  016701  177740                  MOV     FUNC,R1          ;PICK UP FUNCTION
000040  012703  177777                  MOV #177777,R3  ;RESET FOR DAC01
000044  022701  000001                  CMP #1,R1       ;1 IS RESISTANCE
000050  001003                          BNE FREQ
000052  042703  000002                  BIC #2,R3       ;SET UP OHMS
000056  000405                          BR      DORANG
000060  022701  000000          FREQ:   CMP #0,R1       ;0 IS FREQUENCY
000064  001002                          BNE DORANG      ;DEFAULT IS VOLTS
000066  042703  000001                  BIC #1,R3       ;SET UP FREQ

                                ; (2) EVALUATE RANGE

000072  016701  177704          DORANG: MOV     RANGE,R1         ;PICK UP RANGE
000076  022701  000004                  CMP #4.,R1      ;CHECK RANGE
000102  003015                          BGT STORR3      ;OUT OF RANGE - DEFAULT 1KV/1MEG
000104  001003                          BNE NAR         ;NOT AUTO RANGE, EITHER
000106  042703  002000                  BIC #2000,R3    ;SET AUTO RANGE
000112  000411                          BR STORR3
```

```
   000114  022701  000011         NAR:    CMP #9.,R1         ;CHECK RANGE
   000120  002406                         BLT STORR3         ;DEFAULT AGAIN
   000122  012702  000001                 MOV #1,R2          ;RANGE BIT
   000126  006302                 LEFT1:  ASL R2             ;MOVE BIT LEFT ONE
   000130  005301                         DEC R1
   000132  001375                         BNE LEFT1          ;ENOUGH?
   000134  040203                         BIC R2,R3          ;SET RANGE BIT
   000136  010367  177644         STORR3: MOV R3,DAC01       ;SET DVM WORD IN MEMORY

                                  ; (3) EVALUATE CHANNEL

   000142  016701  177636                 MOV     CHAN,R1          ;PICK UP CHANNEL
   000146  002001                         BGE .+4
   000150  005401                         NEG R1             ;MAKE POSITIVE IF NEGATIVE

                                  ; (4) CONVERT FROM BINARY TO BCD 8-4-2-1

           000310                         LIMIT=200.
   000152  162701  000310         PLUS:   SUB #LIMIT,R1      ;MODULO LIMIT
   000156  002375                         BGE PLUS
   000160  062701  000310                 ADD #LIMIT,R1
   000164  005002                         CLR R2             ;FOR RESULT
   000166  012703  000230'                MOV #LIST,R3       ;POINTER
   000172  161301                 SX:     SUB (R3),R1        ;COUNT DOWN
   000174  002403                         BLT AX             ;THROUGH?
   000176  066302  000006                 ADD 6(R3),R2       ;NO, COUNT IT
   000202  000773                         BR SX              ;AND TRY FOR ANOTHER
   000204  061301                 AX:     ADD (R3),R1        ;RESTORE
   000206  005743                         TST -(R3)          ;MOVE POINTER, LOOK FOR ZERO
   000210  001370                         BNE SX             ;NOT ZERO -- NEXT DECADE
   000212  005202                         INC R2             ;RESET ON, START & STEP OFF
   000214  010267  177570                 MOV R2,DAC02       ;SAVE X-BAR CHANNEL INFO
   000220  000207                         RTS     PC

                                  ; BINARY TO BCD CONVERSION TABLES
   000222  000000                         .WORD   0          ;FOR END OF PROG.
```

```
000224  000001                               .WORD   1.
000226  000012                               .WORD   10.
000230  000144                       LIST:   .WORD   100.
000232  000020  000400  010000               .WORD   20.400.10000 ;BCD 1.10.100 LEFT 4 BITS
```

```
                                      ; INITIATE MEASUREMENT PROCESS

000240                                DAQSUP:                                ;JSR PC.DAQSUP
000240   012703   177522                     MOV #SCNCTL.R3  ;SET UP POINTERS
000244   012702   000510'                    MOV #S100U.R2
000250   004567   000000G                    JSR      R5.CTLMDX         ;SET UP DEVICE
000254   000002                              DEV2
000256   013746   177776                     MOV      @#PS.-(SP)        ;SAVE STATUS
000262   012737   000340   177776            MOV      #340.@#PS         ;PRIO 7
000270   016713   177520                     MOV DACQ4.@R3:SHOW TO X-BAR: CHAN & RESET
000274   004712                              JSR PC.@R2
000276   052713   000002                     BIS #2.@R3        ;TURN OFF RESET
000302   004712                              JSR PC.@R2        ;WAIT TIL END OF RESET
000304   012713   000003                     MOV #3.@R3        ;TURN OFF L.L. SET
000310   004712                              JSR PC.@R2        ;FOR SAFETY
000312   005313                              DEC @R3           ;SET START
000314   004712                              JSR PC.@R2
000316   005213                              INC @R3           ;TURN OFF START
                                             ;CHANNEL SHOULD BE SET IN 30 MS FOR GUARD
                                             :                         +8 MS FOR HI-LO
000320   012637   177776                     MOV      (SP)+.@#PS        ;RESTORE OLD STATUS
000324   004567   000000G                    JSR      R5.CTLMDX         ;SET UP DEVICE
000330   000001                              DEV1
000332   016737   177454   177522            MOV DACQ3.@#DVMCTL ;SET UP METER FCN/RANGE
000340   000207                              RTS PC
```

```
                                    ; WAIT ON XBAR CONNECTION

000342                              SENCDE:                         ;JSR PC,SENCDE
000342  012704  000620                      MOV     #400.,R4        ;40*100-US=40-MS
000346  004767  000136              MLOOP:  JSR     PC,S100U
000352  005304                              DEC     R4
000354  003374                              BGT     MLOOP

                                    : ENCODE THE METER.

000356                              ENCODE:                         ;JSR PC,ENCODE
000356  012703  177522                      MOV #DVMCTL,R3  ;SET UP POINTERS
000362  012702  177524                      MOV #CHNID,R2
000366  012704  000000G                     MOV     #CTLMDX,R4
000372  004514                              JSR     R5,@R4          ;SET UP DEVICE
000374  000000                              DEV0
000376  013746  177776                      MOV     @#PS,-(SP)      ;SAVE PS
000402  012737  000340  177776              MOV     #340,@#PS       ;PRIO 7
000410  032712  040000                      BIT #40000,@R2  ;MAKE SURE METER WILL
000414  001775                              BEQ .-4         ;ACCEPT ENCODE
000416  004514                              JSR     R5,@R4          ;SET UP DEVICE
000420  000001                              DEV1
000422  042713  004000                      BIC #4000,@R3   ;ENCODE
000426  004767  000056                      JSR PC,S100U
000432  052713  004000                      BIS #4000,@R3   ;BACK OFF
000436  004514                              JSR     R5,@R4          ;SET UP DEVICE
000440  000000                              DEV0
000442  032712  040000              MEWAIT: BIT #040000,@R2 ;STALL FOR METER
000446  001375                              BNE     MEWAIT          ;WAITING FOR DROP
000450  032712  040000              REWAIT: BIT #040000,@R2 ;LOOK FOR RECORD SIGNAL
000454  001775                              BEQ REWAIT      ;WAITING FOR RISE
000456  012637  177776                      MOV     (SP)+,@#PS      ;RESTORE STATUS
000462  004514                              JSR     R5,@R4          ;SET JP DEVICE
000464  000001                              DEV1
000466  013767  177524  177324              MOV @#DVLO,DVMLO        ;GET MEASUREMENT
000474  004514                              JSR     R5,@R4          ;SET UP DEVICE
```

```
000476  000002                              DEV2
000500  013767  177524  177310              MOV @#DVHI,DVMHI          ;BOTH WORDS
000506  000207                              RTS PC           ;RETURN TO CALLER

000510  012705  000022             S100U:   MOV     #18.,R5           ;100-US STALL
000514  005305                     S100UL:  DEC     R5
000516  003376                              BGT     S100UL
000520  000207                              RTS     PC
```

```
000522  162706  000012          BCDTOF: SUB    #12,SP                 ;MAKE A PLACE
000526  010600                          MOV    SP,R0                  ;FOR ASCII STRING
000530  016703  177270                  MOV    DVM2,R3                ;GET 1ST WORD
000534  004767  000066                  JSR    PC,C.000               ;CONVERT TO ASCII
000540  016703  177256                  MOV    DVM1,R3                ;GET 2ND WORD
000544  004767  000056                  JSR    PC,C.000               ;CONVERT TO ASCII
000550  012720  026505                  MOV    #"E-,(R0)+             ;PUT IN EXP. INDIC.
000554  016703  177244                  MOV    DVM2,R3                ;NOW FOR EXPONENT
000560  012705  000001                  MOV    #1,R5                  ;ONE BCD DIGIT
000564  004767  000054                  JSR    PC,C.001               ;CONVERT EXP
000570  120227  000066                  CMPB   R2,#'6                 ;>6 IS OVERFLOW
000574  003403                          BLE    .+10                   ;NO
000576  112760  000053  177776          MOVB   #'+,-2(R0)             ;E+9 FOR OVERFLOW
000604  112710  000054                  MOVB   #',,@R0                ;PUT IN TERMINATOR
000610  010601                          MOV    SP,R1                  ;SOURCE
000612  104023                          ATOF                          ;CONVERT IT
000614  011167  177206                  MOV    (R1),METER             ;PROTOTYPE
000620  062706  000012                  ADD    #12,SP                 ;GIVE BACK SPACE
000624  000207                          RTS    PC                     ;RETURN TO USER

000626  012705  000001          C.000:  MOV    #1,R5
000632  004767  000006                  JSR    PC,C.001
000636  005300                          DEC    R0                     ;IGNORE 1ST BCD DIGIT
000640  012705  000003                  MOV    #3,R5                  ;CONVERT OTHER 3
000644  005002                  C.001:  CLR    R2                     ;RESULT
000646  012704  000004                  MOV    #4,R4                  ;4 BITS
000652  006103                          ROL    R3        ;<-          ;GET A BIT
000654  006102                          ROL    R2        ;  I         ; IN R2
000656  005304                          DEC    R4        ;  I         ;  4 BITS
000660  003374                          BGT    .-6       ;->          ;   TOTAL
000662  062702  000060                  ADD    #60,R2                 ;MAKE ASCII
000666  110220                          MOVB   R2,(R0)+               ;PUT IN RESULT
000670  005305                          DEC    R5
000672  003364                          BGT    C.001
000674  000207                          RTS    PC
```

CTLMDX

Controls Multiplexer Status

```
                                ;
                                ; DR-11A MULTIPLEXER/DEMULTIPLEXER CONTROLLER
                                ;
                                ; REV: 8/3/73
                                ;
                                ; CONTENTS:
                                ;       1. CTLMDX
                                ;
                                ; THIS MODULE SWITCHES THE DR-11A AMONG THE
                                ; SEVERAL DEVICES ATTACHED TO IT
                                ;
                                ; CALLING CONVENTION:
                                ;
                                ;       JSR     R5,CTLMDX
                                ;       .WORD   <DEVICE #>      ;<DEVICE #>:=0,1,2,3
                                ;
                                        .TITLE  CTLMDX
                                        .GLOBL  CTLMDX
        000000'                         .CSECT

        000000                  R0      =       %0
        000001                  R1      =       %1
        000002                  R2      =       %2
        000003                  R3      =       %3
        000004                  R4      =       %4
        000005                  R5      =       %5
        000006                  SP      =       %6
        000007                  PC      =       %7
        177776                  PS      =       177776
        000340                  PRIO7   =       340
        177520                  MDXCTL  =       177520
        177522                  DMXOUT  =       177522
        177524                  MUXIN   =       177524

000000  010446                  CTLMDX: MOV     R4,-(SP)        ;SAVE REGISTERS
000002  010246                          MOV     R2,-(SP)
```

```
   000004  010046                              MOV     R0,-(SP)
   000006  012702  177520                      MOV     #MDXCTL,R2        ;^DR11A CSR
   000012  012500                              MOV     (R5)+,R0          ;GET NEW DEVICE #
   000014  006300                              ASL     R0                ;SLOT #
   000016  013746  177776                      MOV     @#PS,-(SP)        ;SAVE STATUS
   000022  052737  000340  177776              BIS     #PRIO7,@#PS       ;SET UP PRIO7
   000030  052712  000001                      BIS     #1,(R2)           ;LATCH IT UP
   000034  011204                              MOV     (R2),R4           ;GET CURRENT DEVICE
   000036  042704  177771                      BIC     #177771,R4        ;CLEAN IT UP
   000042  012264  000102'                     MOV     (R2)+,MCSTOR(R4);SAVE CURRENT CSR
   000046  011264  000112'                     MOV     (R2),MDSTOR(R4)  ; AND CURRENT DATA
   000052  016012  000112'                     MOV     MDSTOR(R0),(R2)  ;REPLACE W/ OLD DATA
   000056  016042  000102'                     MOV     MCSTOR(R0),-(R2); AND OLD CSR
   000062  042712  000001                      BIC     #1,(R2)           ;UNLATCH THE SWITCHES
   000066  012637  177776                      MOV     (SP)+,@#PS        ;RESTORE PS
   000072  012600                              MOV     (SP)+,R0          ;RESTORE REGS
   000074  012602                              MOV     (SP)+,R2
   000076  012604                              MOV     (SP)+,R4
   000100  000205                              RTS     R5                ;RETURN
   000102  000001  000003  000005  MCSTOR:     .WORD   1,3,5,7           ;PLACE FOR CSRS
   000110  000007
   000112  000000  000000  000000  MDSTOR:     .WORD   0,0,0,0           ;PLACE FOR DATA
   000120  000000
           000001'                             .END
```

POWER FAIL

Stores Working Register on Power Loss

Resets Hardware to Status Prior to Power Loss
on Power Up

Restores Working Registers on Power Up

```
                                ;
                                ; POWER FAIL/RESTART ROUTINE
                                ;
                                ; REV: 7/30/73
                                ;
                                ; CONTENTS:
                                ;       1. PFAIL
                                ;
                                ; THIS MODULE PROVIDES POWER FAILURE AND POWER RESTART
                                ; CAPABILITIES FOR THE CONTROLLER PROGRAM. IT RESTORES
                                ; AND SAVES ALL PERTINENT STATUS REGISTERS. I/O IN
                                ; PROGRESS AT TIME OF POWER FAIL MAY SUFFER DROPPED
                                ; DATA.  THE D/A CONVERTER IS RESTORED ON POWER UP.
                                ;
                                ; VARIABLES:
                                ;
                                ; NPF   (SWI) COUNT OF NUMBER OF POWER FAILURES
                                ; PFLAG (SWI) FLAG: 0=POWER DOWN. -1=POWER UP
                                ; SAVESP(SWI) STORAGE FOR STACK POINTER DURING PWR. OFF
                                ;
                                        .TITLE  PFAIL
                                        .GLOBL  NPF

                                        .GLOBL  CTLMDX,DAQSUP

        000000                  DEV0    =       0
        177520                  MDXCTL  =       177520
        177522                  DMXOUT  =       177522
        177560                  TKS     =       177560
        177564                  TPS     =       177564
        177550                  PRS     =       177550
        177554                  PPS     =       177554

                                ; REGISTER ASSIGNMENTS

        000000                  R0      =       %0
```

```
        000001          R1      =       %1
        000002          R2      =       %2
        000003          R3      =       %3
        000004          R4      =       %4
        000005          R5      =       %5
        000006          SP      =       %6
        000007          PC      =       %7

        177776          PS      =       177776

        000000                  .ASECT
        000024          .       =       24      ;POWER FAIL VECTOR
000024  000006'                 PFAIL
000026  000340                  340
```

```
          000000'                                .CSECT
   000000 000000                       NPF:      .WORD    0
   000002 000000                       PFLAG:    .WORD    0
   000004 000000                       SAVESP:   .WORD    0

   000006 005767  177770               PFAIL:    TST      PFLAG            ;UP OR DOWN?
   000012 001031                                 BNE      PUP              ;UP..
   000014 010546                                 MOV      R5,-(SP)
   000016 010446                                 MOV      R4,-(SP)
   000020 010346                                 MOV      R3,-(SP)
   000022 010246                                 MOV      R2,-(SP)
   000024 010146                                 MOV      R1,-(SP)
   000026 010046                                 MOV      R0,-(SP)
   000030 013746  177564                         MOV      @#TPS,-(SP)
   000034 013746  177560                         MOV      @#TKS,-(SP)
   000040 013746  177550                         MOV      @#PRS,-(SP)
   000044 013746  177554                         MOV      @#PPS,-(SP)
   000050 013746  177520                         MOV      @#MDXCTL,-(SP)
   000054 004567  000000G                        JSR      R5,CTLMDX
   000060 000000                                 DEV0                      ;SAVE ALL DEVICES
   000062 010667  177716                         MOV      SP,SAVESP        ;SAVE THE STACK
   000066 012767  177777  177706                 MOV      #-1,PFLAG        ;FLAG FOR UP
   000074 000000                                 HALT                      ;WHOA..

   000076 016706  177702               PUP:      MOV      SAVESP,SP
   000102 005067  177674                         CLR      PFLAG
   000106 012737  000004  177520                 MOV      #4,@#MDXCTL      ;RESTORE XBAR
   000114 012737  000003  177522                 MOV      #3,@#DMXOUT      ;RESET OFF
   000122 004567  000000G                        JSR      R5,CTLMDX        ;RESTORE D/A
   000126 000000                                 DEV0
   000130 004767  000000G                        JSR      PC,DAQSUP        ;RESTORE DACQ
   000134 011601                                 MOV      (SP),R1          ;GET OLD DEV
   000136 042701  177771                         BIC      #177771,R1       ;CLEAN UP
   000142 006201                                 ASR      R1               ; GET INTO SHAPE
   000144 010167  000004                         MOV      R1,PU.01         ;AND INTO PLACE
   000150 004567  000000G                        JSR      R5,CTLMDX        ;RESTORE DEVICE AT PDOWN
```

```
000154  000000                  PU.01:  .WORD   0                ;DEVICE # HERE
000156  012637  177520                  MOV     (SP)+,@#MDXCTL   ;FINISH
000162  012637  177554                  MOV     (SP)+,@#PPS
000166  012637  177550                  MOV     (SP)+,@#PRS
000172  012637  177560                  MOV     (SP)+,@#TKS
000176  012637  177564                  MOV     (SP)+,@#TPS
000202  012600                          MOV     (SP)+,R0
000204  012601                          MOV     (SP)+,R1
000206  012602                          MOV     (SP)+,R2
000210  012603                          MOV     (SP)+,R3
000212  012604                          MOV     (SP)+,R4
000214  012605                          MOV     (SP)+,R5
000216  005267  177556                  INC     NPF              ;COUNT THE FAILURE
000222  000002                          RTI                      ;RESUME PROCESSING

        000001'                         .END
```

APPENDIX C

The following computer program written in BASIC was used to plot and statistically analyze the data obtained during a digitally controlled deposition. Similar in capability to the program presented in Appendix A, this software package does not have the ability to monitor the deposition parameters as did the above material.

```
01 REM...PROGRAM TO PLOT CONTROLLER OUTPUT
02 REM...OPTIONS REQ: H,O        11/2/74
10 DIM R(240),D(240)
15 GOTO 500
50 LET U1=0
55 LET U=EXF(4,0)
60 IF U=0 THEN 100
65 FOR I=1 TO U
68 IF U1=240 THEN 100
70 LET U1=U1+1
75 LET R(U1)=EXF(4,I):LET D(U1)=EXF(4,I+3)
80 NEXT I
85 GOTO 55
100 LET Y2=9999/40:LET X2=9999/240
110 LET P=EXF(25,0,R1*Y2)+EXF(24,1)+EXF(26,9999,0)+EXF(24,0)
115 LET Y=R(4)*Y2:LET X=4*X2
120 IF Y>9999 THEN LET Y=9999
125 IF Y<0 THEN LET Y=0
130 LET P=EXF(25,X,Y)+EXF(24,1)
140 FOR I=5 TO U1
150 LET Y=R(I)*Y2:LET X=I*X2
155 IF Y>9999 THEN LET Y=9999
160 IF Y<0 THEN LET Y=0
165 LET P=EXF(25,X,Y)
170 NEXT I
175 LET P=EXF(24,0)
190 PRINT"INPUT MAX D/A SETTING...IF UNKNOWN ENTER 0";:INPUT H
195 IF H<>0 THEN 220
200 LET H=1E-6
205 FORI=4 TO U1
210 IF D(I)>H THEN LET H=D(I)
215 NEXT I
216 PRINT"MAX D/A SETTING="H"ENTER DESIRED VALUE";:INPUT H
220 LET L=H-200
225 PRINT"INSTALL RED PEN & <CR> TO BEGIN";:INPUT A2
230 LET X3=9999/240:LET Y3=9999/200
235 LET X2=4*X3:LET Y2=(D(4)-L)*Y3
240 IF Y2>9999 THEN LET Y2=9999
245 IF Y2<0 THEN LET Y2=0
250 LET P=EXF(25,X2,Y2)+EXF(24,1)
255 FOR I=5 TO U1
256 IF I>240 THEN 300
260 IF D(I)=D(I-3) THEN 295
265 LET X=I*X3:LET Y=(D(I)-L)*Y3
270 IF Y>9999 THEN LET Y=9999
275 IF Y<0 THEN LET Y=0
280 LET Y4=Y-Y2:LET Y2=Y
285 LET X4=X-X2:LET X2=X
290 LET P=EXF(26,X4,0)+EXF(26,0,Y4)
295 NEXT I
300 LET P=EXF(24,0)
305 PRINT"INPUT STATISTICAL RANGE";:INPUT L2,U2
310 LET R5=U2-L2+1:LET R6=0:LET R7=0:LET R8=0
```

```
315 FOR I=L2 TO U2
320 LET R6=R(I)*R(I)+R6
325 LET R7=R(I)+R7
330 NEXT I
335 LET M=R7/R5
340 FOR I=L2 TO U2
345 LET R8=ABS(R(I)-M)+R8
350 NEXT I
355 LET R8=R8/(R5-1)
360 LET S=SQR((R6-(R7^2/R5))/(R5-1))
365 GOTO 530
385 PRINT"DATE & #";:INPUT M1,D1,Y1,N1
390 PRINT"MATERIAL";:INPUT T1
395 PRINT"RATE";:INPUT R1
400 PRINT"INSTALL BLUE PEN & <CR> TO BEGIN";:INPUT A1
405 LET P=EXF(24,0)+EXF(25,0,0)+EXF(24,1)
410 FOR I=1 TO 3
415 LET P=EXF(26,2500,0)+EXF(26,0,100)+EXF(26,0,-100)
420 NEXT I
425 LET P=EXF(25,9999,0)
430 FOR I=1 TO 3
435 LET P=EXF(26,0,2500)+EXF(26,-100,0)+EXF(26,100,0)
440 NEXT I
445 LET P=EXF(25,9999,9999)
450 FOR I=1 TO 3
455 LET P=EXF(26,-2500,0)+EXF(26,0,-100)+EXF(26,0,100)
460 NEXT I
465 LET P=EXF(25,0,9999)
470 FOR I=1 TO 3
475 LET P=EXF(26,0,-2500)+EXF(26,100,0)+EXF(26,-100,0)
480 NEXT I
485 LET P=EXF(25,0,0)+EXF(24,0)
490 GOTO 50
500 PRINT"INPUT DATE OF DEPOSITION...M,D,Y";:INPUT M1,D1,Y1
505 PRINT"INPUT RUN NUMBER...";:INPUT N1
510 PRINT"INPUT TYPE MATERIAL...KEY";
512 PRINT"   1-CHROMIUM,2-SILVER,3 TIN SELENIDE";
515 INPUT T1
520 PRINT"INPUT DESIRED RATE...";:INPUT R1
525 GOTO 400
530 PRINT:PRINT:PRINT:PRINT
535 PRINT"TEST DATE..."M1"/"D1"/"Y1"#"N1
540 PRINT"DEPOSITION MATERIAL...";
545 IF T1=1 THEN PRINT"CHROMIUM"
550 IF T1=2 THEN PRINT"SILVER"
555 IF T1=3 THEN PRINT"TIN SELENIDE"
560 PRINT"DEPOSITION MADE IN NRC VACUMM SYSTEM"
570 PRINT"X AXIS SCALED 0 TO 240 (SECS)"
575 PRINT"STATISTICAL RANGE "L2"TO"U2
580 PRINT"STANDARD DEVIATION "S
585 PRINT"MEAN DEVIATION "R8
590 PRINT"MEAN VALUE "M
595 PRINT"RATE AXIS (BLUE) SCALED 0 TO 40"
600 PRINT"D/A AXIS (RED) SCALED"L"TO"L+200
605 PRINT:PRINT:PRINT:PRINT
610 GOTO 385
```

APPENDIX D

The following served as a guide to assist a person nonfamiliar with the execution of the digital controllers software package. It does require familiarization with the digital processor and associated peripheral hardware. The peripheral hardware not only includes items such as the high speed reader/punch, data acquisition unit and digital plotter, but also requires a working knowledge of the vacuum system, SCR power controller, and other vacuum deposition hardware.

Not included in the procedure for execution of the controller program is the technique used to obtain a suitable value for the Final Rise value. This value can be determined experimentally with the aid of the digital controller software package.

By inputting a large soak time such as a 1000 seconds, a small rise time such as 10 seconds, and a Final Rise smaller than required for deposition, the system will quickly reach the soak level. Once in the soak mode, the value of the soak setting can be incremented via the teletype and the command "LET SOAK POWER=". Incrementing the soak power until a deposition rate is obtained and reducing the value until the rate ceases will result in a Final Rise value equal to the Soak Power setting.

PROCEDURE FOR EXECUTING CONTROLLER PROGRAM

1) Load Controller Program with absolute loader at address 037500. (137500 if full memory capability exists)

2) Program will load and have the following response to which you will reply thusly:

Computer	Operator	Remarks
*	21472/	
000000	1 or 4 (CR)	The sample rate 1-SnSe and other low conductivity substances; 4-Ag and other metals
*	14006;G	Starts Controller Program

3) Once in the controller program, the following variables need to be input:

   a. RATE SET
   b. Initial Rise
   c. Final Rise
   d. Rise Time - in seconds
   e. Soak Time - in seconds
   f. Deposit Time - in seconds
   g. Max Power
   h. Min Power
   i. B2
   j. Punch On - If punch isn't desired, no input is required

4) To input a variable, strike a "CTRL P"(↑P) and the computer will respond with a colon (:). At that time, similar to BASIC, input LET variable (a-j) = value. For punch routine, poll the computer and type PUNCH ON.

5) Choices on the above variables can be based on the following criteria:

$$\text{Initial Rise} = \frac{\text{Final Rise}}{\text{Rise Time}}$$

$$\text{Max Power} = \frac{\text{RATE SET}}{4}$$

$$\text{Min Power} = -\frac{\text{RATE SET}}{4}$$

B2 = 4

6) To start program, poll the computer and type GO.

7) For Emergency Stop, poll the computer and input X.

8) Other features that might be of interest are the variables that can be requested to be printed on the teletype. Along with the above variables, Sect 3, the following variables can be polled.

   a. CST - Current Soak Time
   b. CRT - Current Rise Time
   c. CDT - Current Deposit Time
   d. RATE - Current Rate being monitored
   e. CRP - Current Rise Power
   f. CSP - Current Soak Power
   g. CDP - Current Deposition Power
   h. SOAK Power - Current Soak Power (used to change the soak value)

9) In case the soak power is too high or soak time is too long, the deposition process can be initiated at any time once the soak level has been reached by polling the computer and inputting DEPOSIT.

10) Once deposition phase has been initiated, it might be desired to set the computer to deposit only a certain thickness of material. To accomplish this task, poll the computer and type LET THICKNESS - "value." Upon striking return, the computer will take its present frequency value, add the value entered, and then stop the process once the combined frequency is reached.

11) Any of the above variables can be changed at any time by polling the computer and inputting the new value.

12) In order to change the Sample Time, poll the computer and input DEBUG. This puts the program back in the state it was in at the beginning of the program. Change the one address (21472) to the desired sample rate. Then return to the controller program with 14006;G. All of the variables that had previously been set have remained unchanged during the sample time change; thus, no initialization is required.

13) Following is a table that depicts values for variables that have been found to work reliably on the NRC System:

	Ag	SnSe
Sample Time	4	1
Initial Rise	270	240
Final Rise	470	440
Rise Time	51	100
Soak Time	100	25
B2	4	4

14) Following is a sample listing for silver being deposited at a desired rate of 10 Hz/sec:

```
*21472/000000 4   (CR)
*14006;G          (CR)

:LET RATE SET = 10

:LET INITIAL RISE = 270

:LET FINAL RISE=470

:LET RISE TIME=51

:LET SOAK TIME=100

:LET DEPOSIT TIME=240

:LET MAX POWER=2.5

:LET MIN POWER=-2.5

:LET B2=4

:PUNCH ON

:GO

DEPOSITION COMPLETED
```

APPENDIX E

Since statistical data, especially the mean and standard deviation, have meaning only if the sample data can be considered as part of a normal distribution, it is necessary to evaluate a typical run to determine if the rate data are part of a normal distribution. Also before a statistical analysis has meaning, the parameter of interest has to demonstrate that it is random in nature; that is, it is aperiodic about the mean value.

Figure E.1 illustrates a typical run which shows both the rate and the D/A settings plotted as a function of time. Disregarding the transient portion of the curve and only evaluating that portion which appears to have become stable, correlation analysis of the data yielded a constant value for all correlation factors from one second to fifty seconds. For the data no periodicity exists that can be measured numerically. This means the rate can be considered to be random about the mean value.

The next hypothesis, to check the statistical behavior of the rate data, is the determination of the distribution of the data about the mean. Separating the data shown into classes which portray the number of rate samples in a given rate interval, a histogram of the rate data, Fig. E.2, can be constructed. By connecting the center points of each class by a smooth line, a distribution function for the rate data can be illustrated. Using (E.1) below and the calculated mean and standard deviation, a normal distribution curve can be plotted along

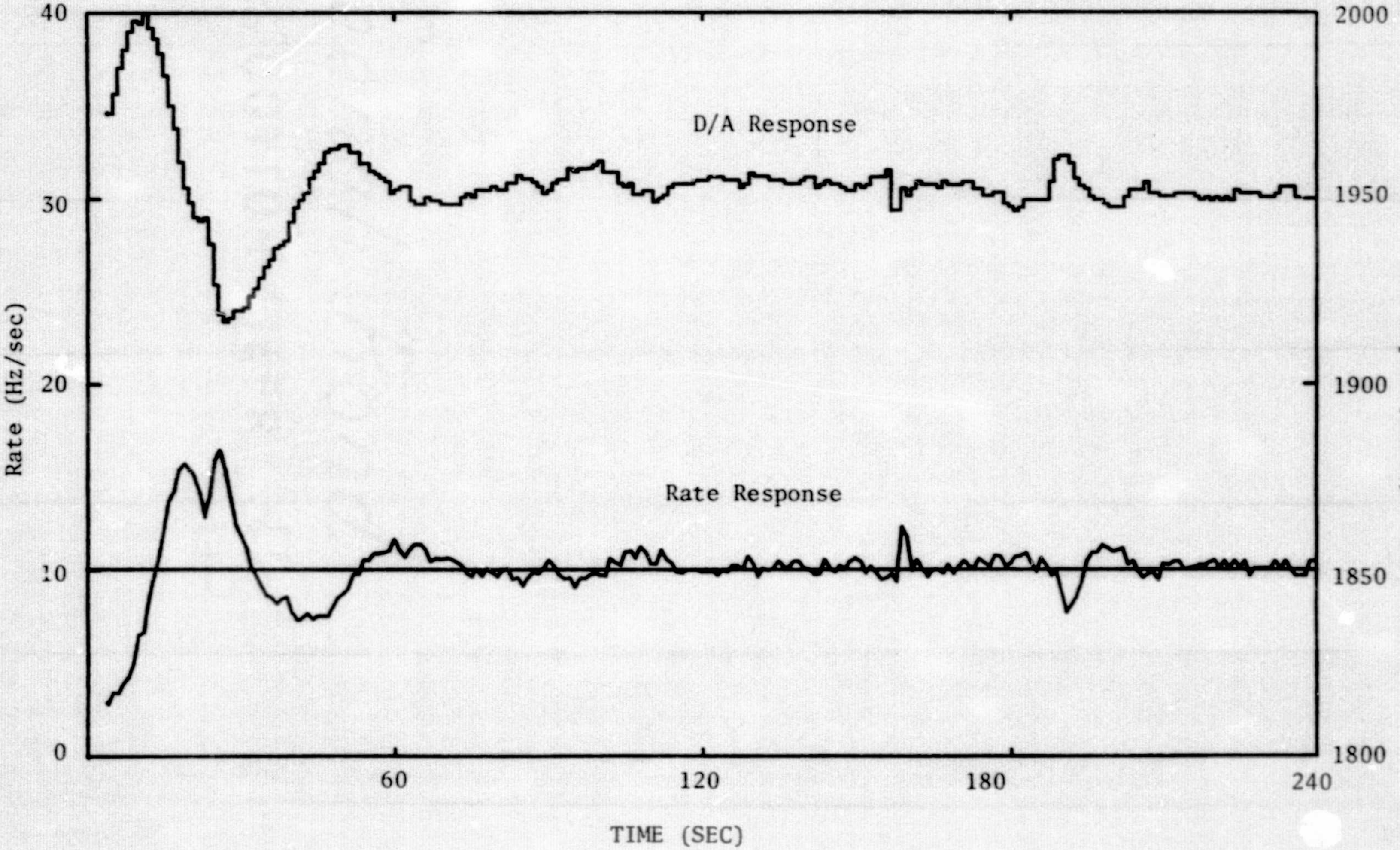

Figure E.1. A Typical Deposition Response

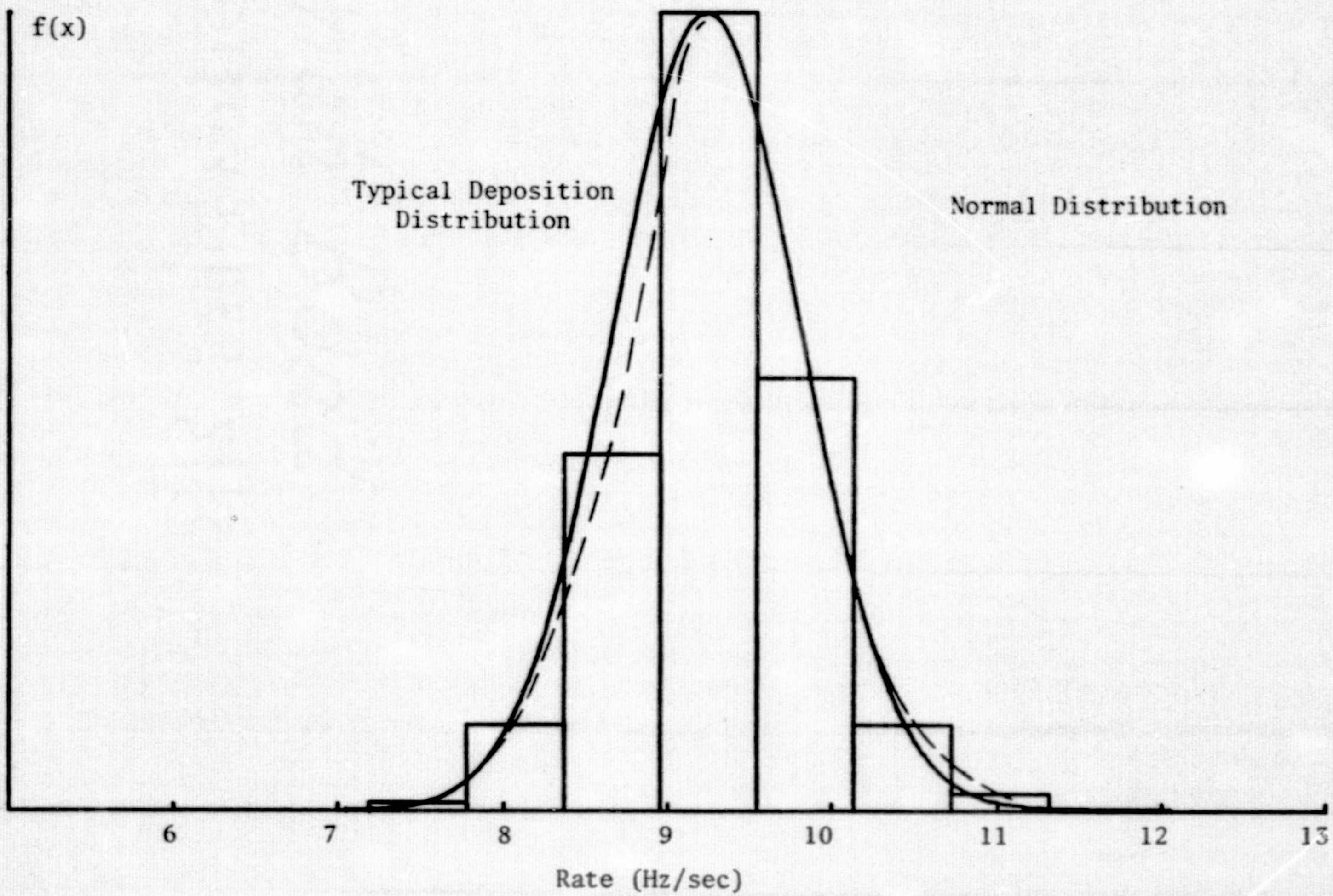

Figure E.2. Histogram and Distribution Curve Versus A Normal Distribution for a Typical Deposition Run with the distribution curve obtained from the histogram. This showed that the rate data can be represented meaningfully by statistical measurements.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\,^{1}/_{2}\left(\frac{x-\mu}{\sigma}\right)^{2}} \tag{E.1}$$

where $f(x)$ = the normal distribution function about the mean μ and standard deviation σ,

μ = mean, and

σ = standard deviation.

Thus, it has been shown that the statistical parameters obtained from the rate data are valid.

APPENDIX F

The following graphs illustrate the variation of the velocity multiplier versus achieved mean standard deviation for the various sample time. Each graph represents a given material deposited at a given rate.

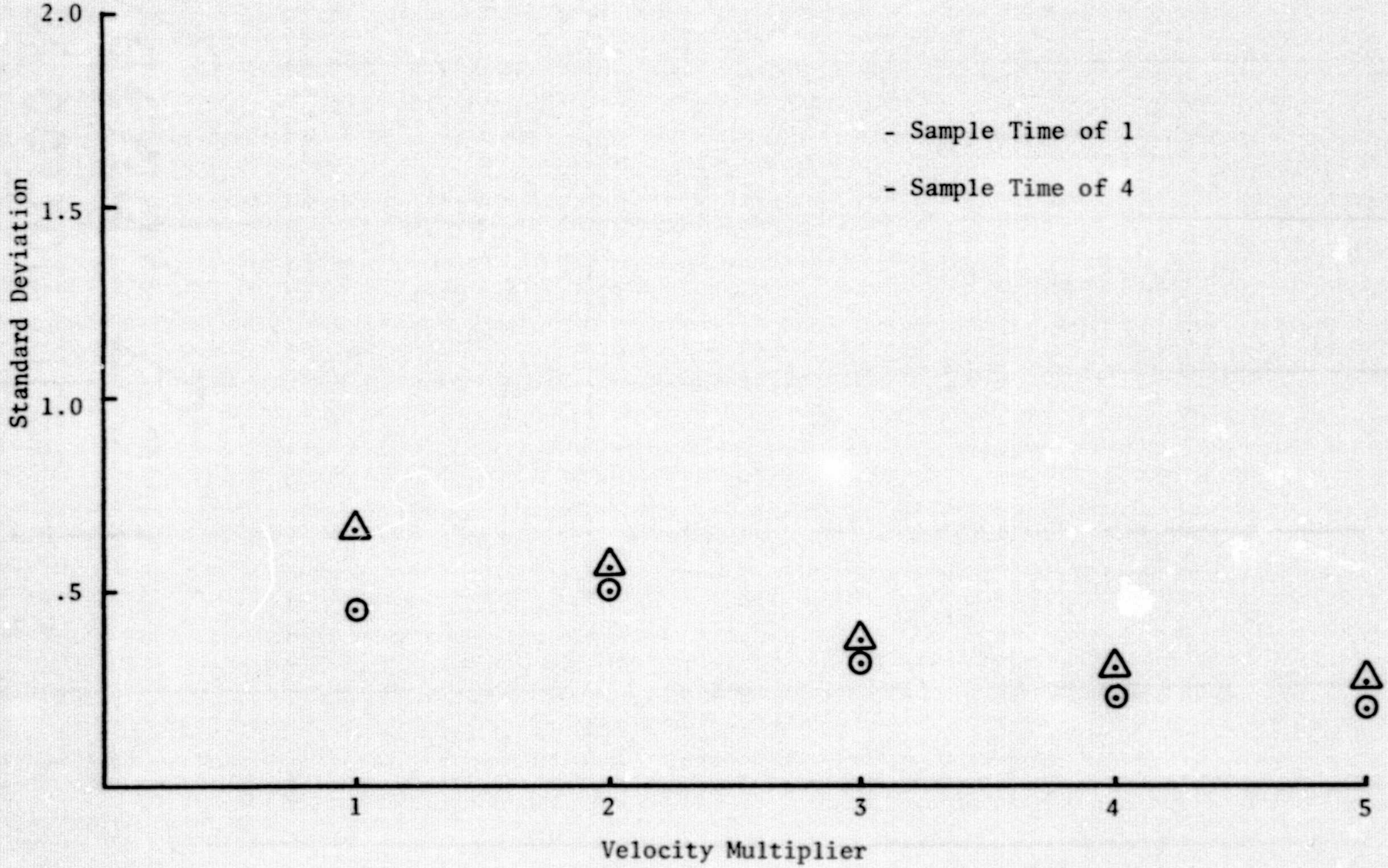

Figure F.1. Standard Deviation versus Velocity Multiplier for Silver Deposited at One Hertz/Sec

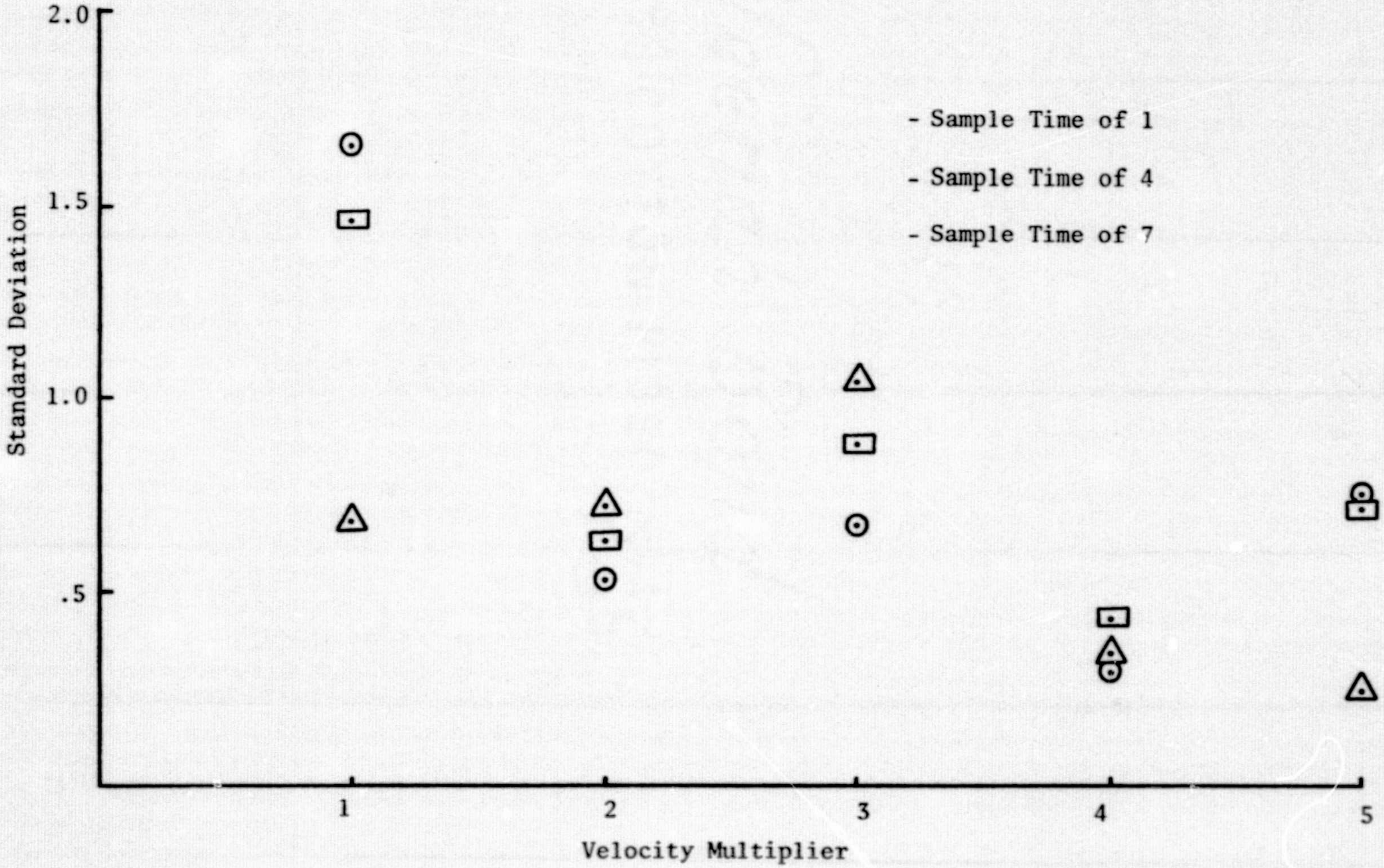

Figure F.2. Standard Deviation versus Velocity Multiplier for Silver Deposited at Five Hertz/Sec

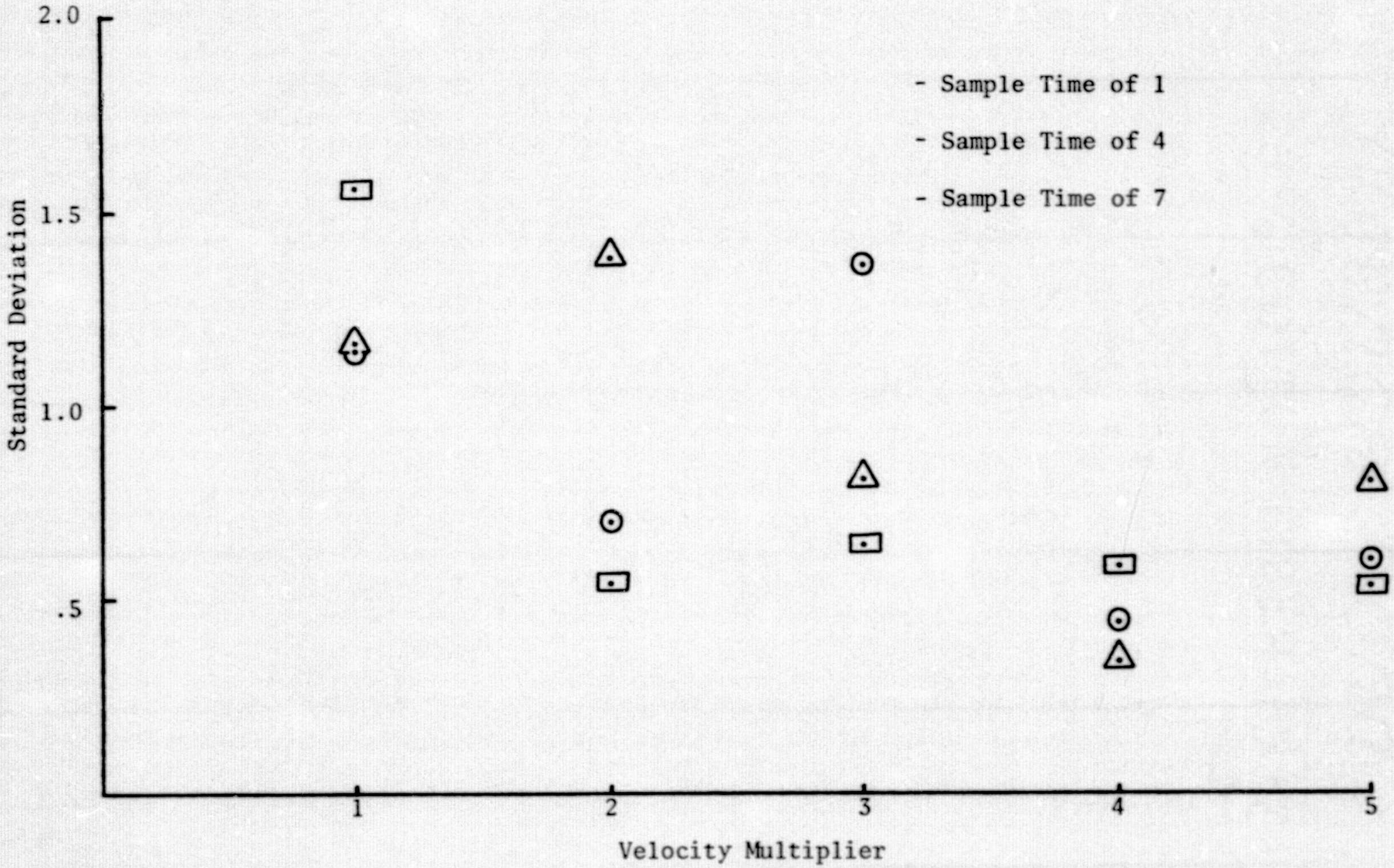

Figure F.3. Standard Deviation versus Velocity Multiplier for Silver Deposited at Ten Hertz/Sec

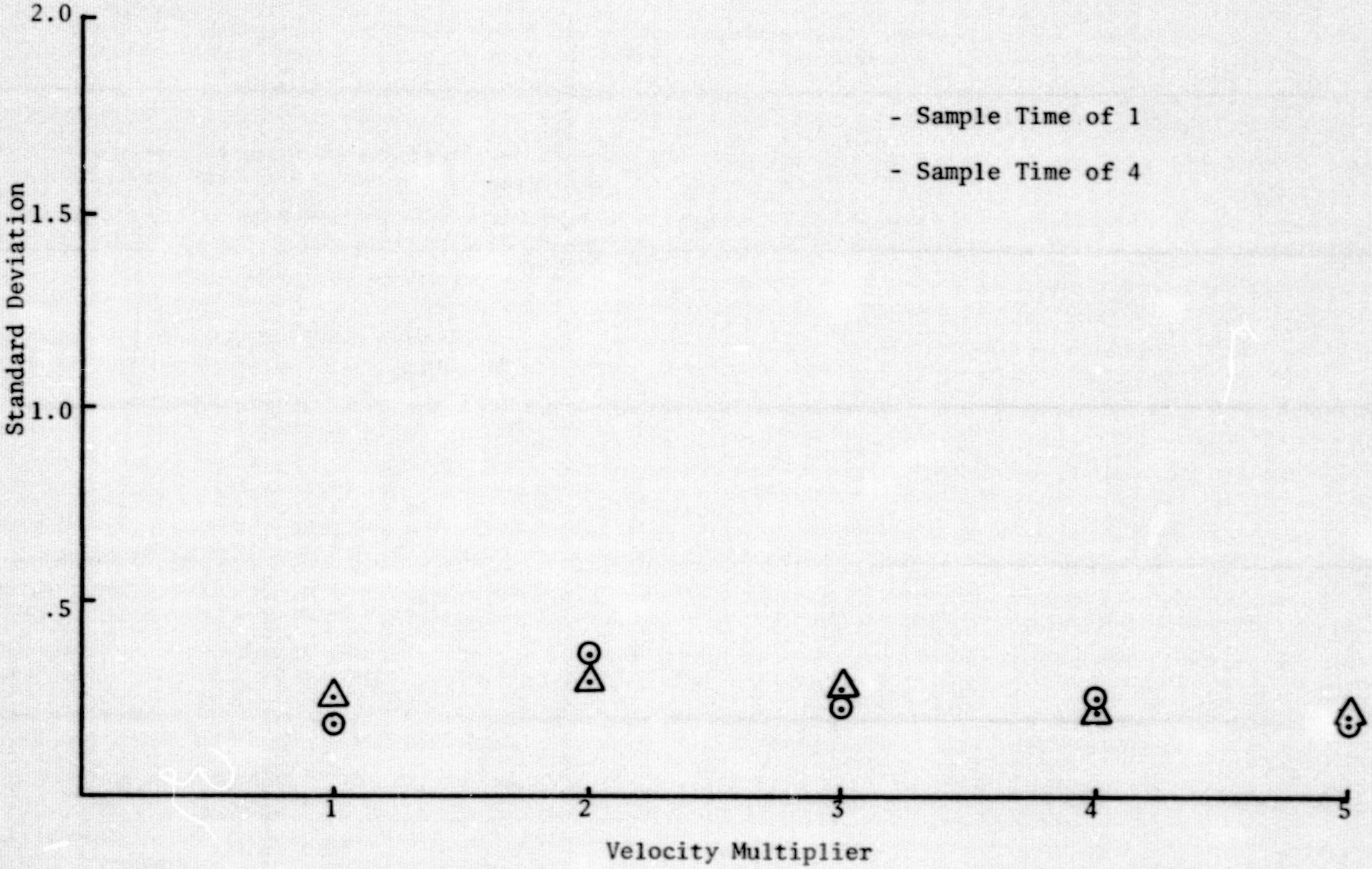

Figure F.4. Standard Deviation versus Velocity Multiplier for Tin Selenide Deposited at One Hertz/Sec

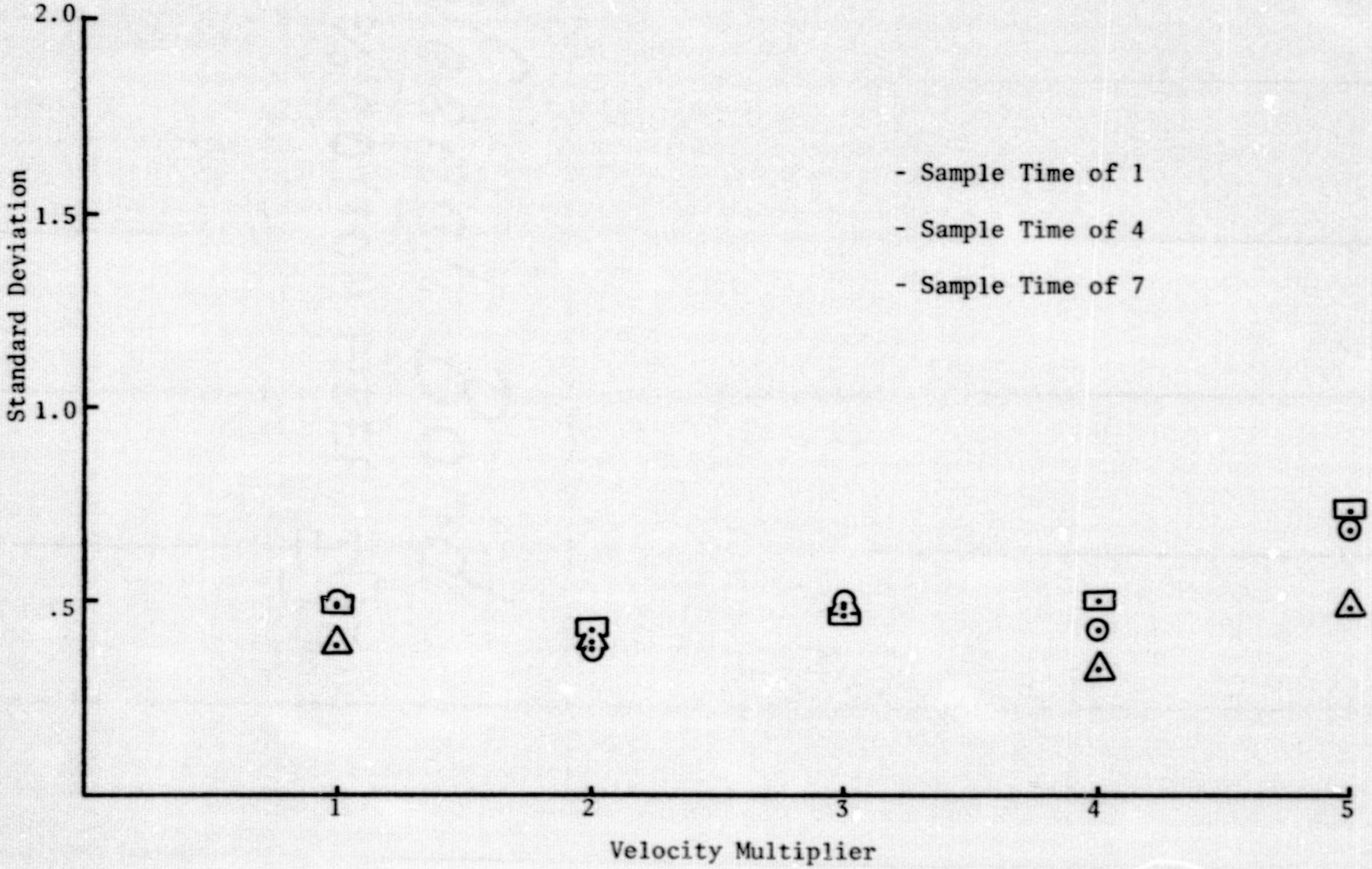

Figure F.5. Standard Deviation versus Velocity Multiplier for Tin Selenide Deposited at Five Hertz/Sec

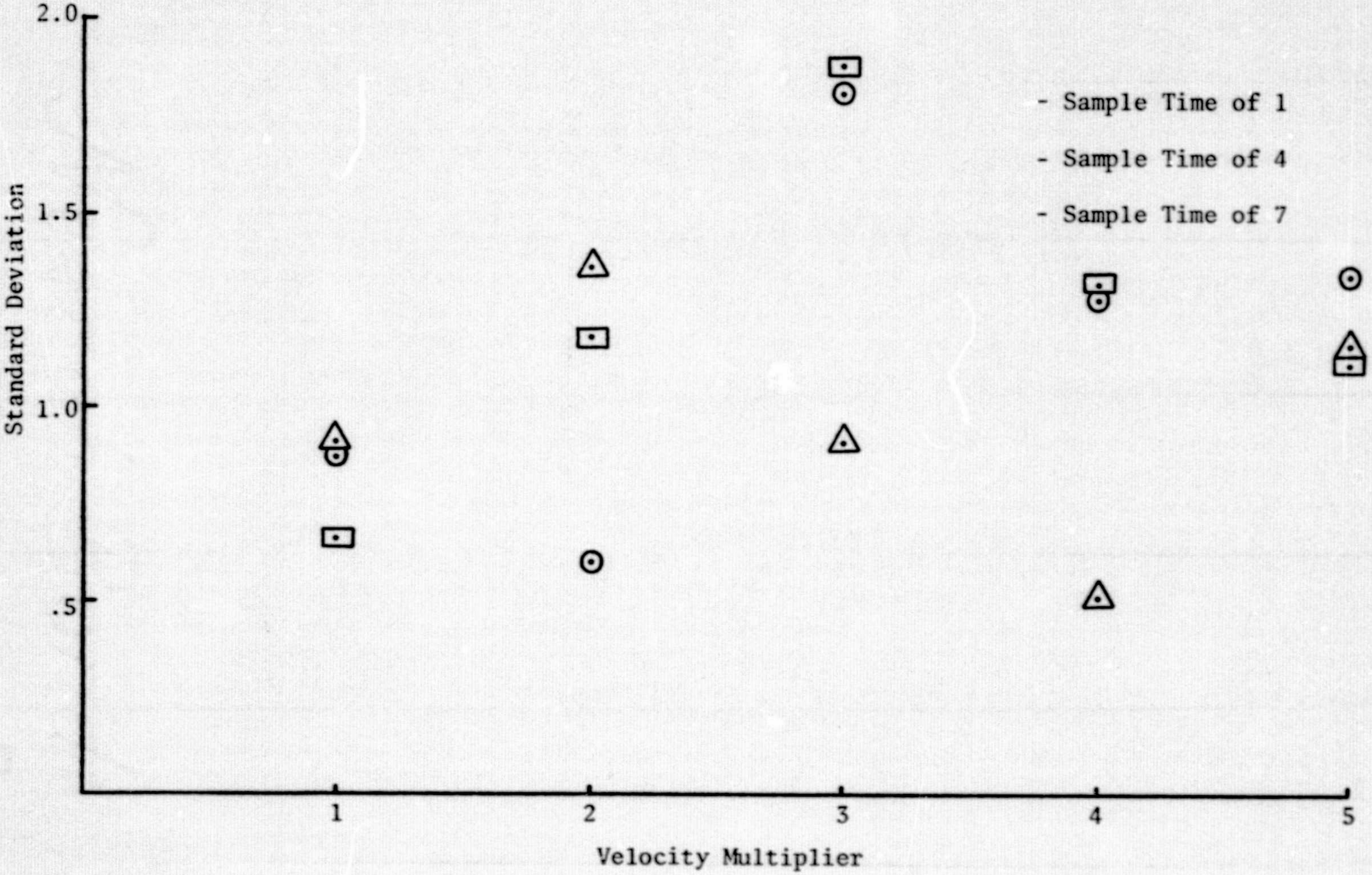

Figure F.6. Standard Deviation versus Velocity Multiplier for Tin Selenide Deposited at Ten Hertz/Sec